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FREEWAY OPERATIONAL FLEXIBILITY CONCEPTS

by

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Thomas W. Rioux
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Pieter Poolman

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IMPLEMENTATION

Concepts developed through this research can provide the basis for choices among freeway design and redesign efforts. Congestion mitigation on urban freeways is becoming an intensively studied topic as traffic demands grow. If implemented, the concepts presented would enable implementation of better incident management processes and freeway bottleneck treatments.

This report was prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

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SUMMARY

Operational flexibility requirements encompass freeway design measures that would enable effective freeway congestion mitigation, including incident management and treatment of bottleneck locations. Freeway congestion mitigation efforts currently being applied are reviewed with respect to how operational flexibility might enable easier and faster implementation. A primary objective of the research was to identify those concepts that would most likely be part of congestion mitigation schemes that are implemented. Therefore, incident management and bottleneck mitigation were selected as two congestion mitigation concepts that are almost certainly to be implemented on virtually all urban freeways. Using video surveillance capabilities at the San Antonio and Houston, Texas, traffic control centers, the researchers examined a large number of freeway incidents. Detailed characterizations of the incidents, emergency responses, and effects upon freeway traffic were prepared. From this analysis, a clear need for a pathway for emergency vehicles to reach incident sites was identified. Additionally, a clear need for a haven for disabled or damaged vehicles was identified. A detailed case study of bottleneck sites on the Austin, Texas, Loop 1 freeway was described. The examination of individual bottleneck sites and recommended solutions, some already implemented, led to development of a series of operational flexibility design concepts.

CHAPTER 1 INTRODUCTION

Since the first freeway designs were developed almost 50 years ago, much has been learned about good and bad design concepts. Design policies developed by the American Association of Transportation Officials, the Federal Highway Administration, the Texas Department of Transportation and other agencies have incorporated many lessons learned. Because most urban freeways currently operating were designed at some earlier stage of freeway design evolution, they collectively represent a vast mixture of good, bad, old, and new design concepts.

Today, and for coming decades, freeway operators must diagnose design-related operational problems and devise "temporary" solutions that will last until the facility can be significantly renovated. As funding becomes available, freeway designers may have opportunities to incorporate new design concepts into freeway renovation or re-build projects.

As new designs are devised, many lessons learned in over 50 years of urban freeway use should certainly be incorporated. One conceptual lesson is that, over many decades of use, urban freeways will serve traffic demands that will change both spatially and through time. Land use adjacent to freeway corridors will change in intensity, sometimes increasing travel demands and sometimes decreasing them. These changes will occur across a time dimension that encompasses decades.

These land-use-induced travel demand changes will create freeway traffic problem areas, sometimes called bottlenecks. Freeway operators will seek solutions to these problems — quick, inexpensive, effective solutions. Freeways of the future should, therefore, be designed to provide operational flexibility. Based on experiences with freeway bottleneck problems, design concepts that enable implementation of solutions should be devised. These design concepts, called operational flexibility design concepts, are the primary subject of this research.

In addition to treating bottleneck problems, operational flexibility design concepts can play a significant role in ameliorating the debilitating effects of freeway incidents. Once considered to be rare events, incidents, including crashes, disabled vehicles, lost cargo, and other obstructions, are routine events on most urban freeways. A major role of traffic control centers in Houston, San Antonio, and soon, other Texas cities, is fast identification of freeway incidents, followed by speedy clearing of the problem and restoration of full freeway flow. A key part of this incident management process is getting emergency service equipment and personnel to the site of the incident. Such accessibility may be extremely difficult if freeway main lanes are full of stopped vehicles, no shoulders are available, and safety barriers prevent access from the freeway right or left sides. Operational flexibility design concepts must be devised that recognize the routine nature of incidents and the criticality of providing emergency access to incident sites.

Recognizing these needs, the researchers have examined a wide range of urban freeway improvement concepts that are being implemented on today's freeway in an effort to increase people-movement potential. These concepts range from high-occupancy vehicle lanes to ramp metering to basic bottleneck treatments. In Chapter 2, these concepts are identified as the types of treatments that operational flexibility design must address. In Chapter 3, incident management is examined through detailed study of almost 100 incidents observed at the San Antonio and Houston, Texas, control centers. Finally, Chapter 4 presents operational flexibility design concepts and their potential relationship to actual bottleneck sites through a case study of the Loop 1 freeway in Austin, Texas.

CHAPTER 2 CONGESTION MITIGATION TECHNIQUES

Increasing traffic congestion, constrained mobility, and environmental concerns (including declining air quality) represent major issues facing many metropolitan areas today. Limited financial resources and right-of-way availability further complicate the situation in numerous areas. Realizing that there is no single solution, transportation professionals and decision makers have been pursuing a variety of techniques and approaches to address those problems. Flexibility in design and operations might offer significant means of easing congestion or at least reducing the trauma associated with solution implementation.

HOV FACILITIES

High-occupancy vehicle (HOV) facilities represent one viable technique being used in many areas to respond to congestion concerns. The priority measures for high-occupancy vehicles implemented throughout North America, while often differing in design and operation, have similar purposes. These facilities, which offer priority treatments to buses, vanpools, and carpools, focus on increasing the person-movement—rather than vehicle-movement—efficiency of a roadway or travel corridor. In North America, approximately forty-nine HOV lanes were in operation on freeways or separate rights-of-way in twenty-two metropolitan areas in the early 1990s (Ref 1). Many more HOV projects are in the planning, design, and construction stages. In response to local problems and needs, a variety of design treatments and operating strategies are used for HOV facilities, resulting in variations in utilization levels and experiences among the different projects.

A primary objective of these priority facilities is to provide HOVs with both travel-time savings and more predictable travel times. These two benefits serve as incentives to induce individuals to choose a higher-occupancy mode. This, in turn, can increase the person-movement capacity of the roadway by carrying more people in fewer vehicles. In some areas, additional incentives such as reduced parking charges or preferential parking for carpools, have been used to further encourage individuals to change their commuting habits. These supporting facilities, services, and programs can influence the success and acceptance of HOV projects. The intent of HOV facilities is not to force individuals into making changes against their will. Rather, the objective is to provide a cost-effective travel alternative that a significant volume of commuters will find attractive enough to persuade them to change from driving alone to using a higher occupancy mode.

Many HOV projects have focused on meeting one or more of three common objectives. These objectives are:

1) Increase the average number of persons per vehicle.
2) Preserve the person-movement capacity of the roadway.
3) Enhance bus transit operations.

High-occupancy vehicle facilities have most commonly been used in roadway corridors that are either at, or near, capacity and where the physical and/or financial feasibility of expanding the roadway is limited. When properly planned and implemented, HOV facilities can offer a number of advantages. However, HOV facilities are not appropriate in all situations, nor does their implementation eliminate the need to also pursue other complementary strategies. The potential use of HOV facilities should be examined thoroughly before any such improvements are made. Some of the advantages of high-occupancy vehicle projects that should be considered in the planning process include the following:

1) Costs
2) Implementation time
3) Staged implementation
4) Lower risk
5) Multi-agency funding
6) Multiple user groups
7) Operating speeds
8) Flexibility
9) Time adjustable operation

HOV facilities on freeways or separate rights-of-way are generally classified into four categories:

1) Exclusive HOV Facility, Separate Right-of-Way
2) Exclusive HOV Facility, Freeway Right-of-Way

3) Concurrent Flow Lane—defined as a freeway lane in the same direction of travel, not physically separated from general-purpose traffic lanes, and designated for exclusive use by HOVs for all or a portion of the day.
4) Contraflow Lane—usually a freeway lane in the off-peak direction of travel, typically the innermost lane, designated for exclusive use by HOVs traveling in the peak direction.

HOV facilities separated by barriers or buffers are generally regarded as the design option that offers more operational benefits than non-separated, or contiguous, HOV facilities. Right-of-way constraints, however, sometimes preclude the separated option. Whether separated or contiguous, the operational differences among the various HOV geometric options are minor when they are compared to the differences between any HOV lane and a mixed-flow lane. The designer should consider the operation of the HOV facility when designing the facility. Operational characteristics such as part-time operation, reversible flow, or contraflow operations are essential to the configuration being considered.

General design criteria from CalTrans include:

1) Horizontal stopping sight distance—Where conformance is not feasible owing to median barriers, the height of the object can be increased from 0.5 foot to 2.5 feet (the assumed height of a car's taillights) above the pavement surface.
2) Decision stopping sight distance—This should be provided to the nose of all HOV drop ramps, flyovers, and freeway-to-freeway connectors.
3) Vertical clearance—The required vertical clearance for freeways and expressways is 16.5 feet.
4) Drainage—The narrow median widths on retrofit HOV facilities often create problems in super-elevated areas or when the HOV lane slopes toward the media. A water-carrying barrier, a slotted pipe, or an approved alternate must be provided in these areas.
5) Structural section—The structural section of HOV lanes on new facilities should be equal to that of the adjacent mixed-flow lane unless a greater thickness is required owing to anticipated high bus usage. The existing shoulder or paved

median should not be converted to an HOV lane unless a material investigation concludes that the projected life of the existing pavement is at least 6 years.

6) Lane width—Twelve-foot lanes are preferable. Eleven-foot lanes may be acceptable if justified by an engineering analysis. However, the outside mixed-flow lane should remain at 12 feet unless truck volume is less than 3 percent. When adjacent to a wall or barrier, shoulder widths between 4 feet and 8 feet on mainline HOV facilities should be avoided (except as spot locations).

A recent development in HOV design is direct HOV connectors at intersecting freeways. Because few operational or support data available for planning and designing direct connectors is lacking, these guidelines will become more definitive as operational experiences accumulate.

Direct ramp connectors to provide ingress and egress between HOV lanes and conventional highways, streets, roads, transit facilities, or park-and-ride facilities are sometimes referred to as HOV drop ramps. As is the case with freeway-to-freeway HOV connectors, operational data for existing drop ramps is lacking for planning and design purposes. It may be difficult, particularly in retrofit situations, to fit HOV drop ramps into the available space.

In terms of the decision-making process and institutional arrangements associated with HOV projects, Turnbull (Ref 2) analyzed selected HOV facilities at six case study sites. Facilities in Houston (Katy Freeway I-10W), Texas; Minneapolis-St. Paul (I-394), Minnesota; Orange County (Route 55), California; Pittsburgh (I-279), Pennsylvania; Seattle (I-5N), Washington; and Washington, D.C./northern Virginia (Shirley Highway I-395) represented the selected case study sites. Common characteristics that led to the decision to implement the HOV facilities include the following:

1) An awareness of the need to address increasing traffic congestion problems in the corridor had developed.
2) No decision had been made on the development of a fixed-guideway transit system in the corridor where the HOV facility was ultimately developed.
3) HOV projects in many of the case study sites were considered and implemented as part of larger highway improvement projects.

4) Individuals in positions of authority in highway and transit agencies supported the HOV project concept and promoted it through the project development and implementation process.
5) Legislative or agency policies and directives played an important role in the decision-making process in some of the case studies.

Similarities during the development of the actual projects include the following:

1) One agency, usually the state department of transportation or highway department, had overall responsibility for implementing the HOV project. However, transit and other agencies were often involved in some aspects of planning, designing, and, in a limited number of cases, financing the project.
2) Interagency cooperation, including the use of multi-agency project management groups, played an important part in the coordinated implementation of most of the case study HOV projects.
3) Multiple funding sources and innovative financing approaches were utilized with some of the case study HOV projects.
4) Support from FHWA and UMTA was evident, although in different degrees, in the development of many case study HOV facilities.
5) HOV projects provide flexibility to respond to changing travel demands, needs and policies. Changes in operating policies have occurred at most of the case study sites.

During the peak hours of 1992, the HOV lanes in the case study sites were moving approximately 60 to 350 percent more persons per lane than the freeway general-purpose lanes. The HOV lanes also resulted in an increase in the average vehicle occupancy level for the total freeway facility in those corridors with HOV facilities. Furthermore, the opening of HOV lanes resulted in reduced bus travel times and improved bus on-time performance. In Houston, on average, the peak-hour bus operating speeds almost doubled, increasing from 26 mph to 54 mph. Response to surveys indicated that HOV lanes have played a significant part in encouraging individuals to change from driving alone to using the bus. For example, in surveys conducted in 1988, 1989, and 1990, between 54 and 76 percent of the bus riders using the Houston HOV lanes responded that the opening of the HOV lanes was very important in their decision to ride a bus.

Turnbull (Ref 3) also reports on the development of a suggested approach and procedure for evaluating freeway HOV projects. It is proposed that HOV facilities be analyzed using the following evaluation measures:

1) Person-movement capacity of the freeway facility
2) Bus service operating efficiencies
3) Travel-time savings and trip-time reliability
4) Air quality and energy impacts
5) Per-lane efficiency of the freeway facility
6) Impacts on the operation of the freeway general-purpose lanes
7) Safety
8) Public support
9) Cost effectiveness

As the number of HOV facilities continues to grow, the understanding of issues associated with the planning, design, implementation, and operation of HOV projects has also increased dramatically. However, even with this increased understanding, there are still a number of issues on which experience is lacking, or on which there is disagreement over the most appropriate approach. These issues and some of the areas where additional research is needed include the following:

1) Support Facilities—data from different HOV projects seem to indicate that the presence of park-and-ride lots, transit transfer centers, direct access ramps, and other support facilities enhance the performance of HOV facilities.
2) Support Services—it appears that simply providing an HOV lane is not enough to ensure maximum use. Programs focusing on improved bus service, ridesharing, parking supply, and pricing and travel demand management have all been used in different areas to promote and support HOV facilities. Additional incentives include the guaranteed ride home program, preferential parking and/or reduced parking charges for vanpools and carpools, and monetary incentives or additional vacation time for those using alternative commute modes.

3) Operations and Enforcement—Early consideration of these issues is critical to ensuring that the facility operates in the intended manner and can be easily enforced.

RAMP METERING

Freeway traffic management (FTM) systems have been proposed and implemented in some cities around the country as one traffic management strategy for reducing traffic congestion without adding extra physical capacity to the existing facility. Adding physical capacity to an existing urban freeway is not only extremely costly, but may have serious negative side-effects on the local social and economic environment. Well-designed and maintained ramp metering systems have proven to be an effective FTM tactical component in reducing freeway congestion in large urban areas.

By regulating freeway input flow, ramp metering offers several operational features for improving freeway flow, traffic safety and air quality. Ramp meters are traffic signals placed on freeway entrance ramps that, by judiciously cycling the signal, regulate the ramp flow to the freeway in an objective manner. In the metering mode, ramp meters operate to discharge traffic at a measured rate, based on real-time conditions, thereby protecting the delicate demand-capacity balance at the ramp-merge or downstream bottleneck. As long as mainline traffic demand does not exceed capacity, throughput is maximized, speeds remain more uniform, and congestion-related accidents are reduced. Ramp meters also regulate the ramp traffic in order to break up platoons of vehicles that have been released from nearby signalized intersections. The mainline, even when traffic flow nears capacity, can usually accommodate merging vehicles one or two at a time. On the other hand, when platoons of vehicles attempt to force their way into the freeway traffic, this action creates turbulence that can cause mainline flow to break down.

The types of ramp metering systems implemented reflect the traffic control needs and technology of the times. Most systems were installed before the advent of rugged microprocessor-based computing. Ramp metering systems, as described by Messer, include:

1) Local Pre-timed Control—The simplest form of ramp metering uses the isolated or local pre-timed control mode of operation. Ramp metering volumes are initially based on highway capacity manual methods of analysis, and are then

fine-tuned based on local field observations. Pre-timed signal timing plans are based on observed mainline volumes, merging volumes, and existing ramp volumes. To maintain demand-capacity balance on the freeway, ramp-merging volumes may need to be reduced. Traffic detectors are used only to drive the on/off status of ramp metering signals and are not used to measure or estimate freeway demands or traffic conditions.

2) Local Traffic Responsive Control—The next higher level of control establishes traffic responsive metering rates based on measured freeway traffic conditions upstream of the ramp. The local traffic responsive approach utilizes detectors and a microprocessor to determine the mainline flow in the immediate vicinity of the ramp and ramp demand to select an appropriate metering rate. Traffic responsive metering can be expected to produce results that are on the average 5 to 10 percent better than those of pre-timed metering.
3) Adaptive Local Traffic Responsive Ramp Control—This ramp control mode provides traffic volume and occupancy data from both upstream and downstream detector stations to the ramp-metering controller. The data coming from the two adjacent traffic sensor stations can be used in a variety of ways at the local controller. The primary way is to first determine if the downstream section has stable, non-congested flow. If so, then the upstream detectors operate much as in local traffic responsive control. If not, then the downstream flow is congested and more restricted metering rates are implemented.
4) System Ramp Control—The primary objective is to prevent freeway congestion. The next highest objective is to respond to unexpected congestion in a systems manner. Ramp control is based on overall system capacity considerations rather than just on the capacity at each ramp. System control has either pre-timed system metering or traffic-responsive system metering.

Ramp metering is not a new traffic management concept. Various forms of ramp control were used experimentally in Detroit in the early 1960s. In Chicago, ramp meters have been in operation on the Eisenhower Expressway since 1963. Eight ramp meters installed on the Gulf Freeway in Houston in 1965 operated successfully until freeway reconstruction required their removal in 1975. Over thirty ramp meters operated successfully on the North Central Expressway in Dallas from 1971 until major freeway reconstruction forced most of them to be removed in 1990. In Los Angeles, ramp metering began in 1968. The system has been expanded continually, such that there are now over 900 meters in operation in metropolitan Los Angeles, making it the largest system in the country. These metering systems vary from fixed-time operation at a single ramp to the responsive control of every ramp along many miles of a freeway. One measure of the effectiveness of ramp metering is the fact that nearly every existing system has been, or is proposed to be, expanded.

The successful use of ramp meters does not require large systems. In Austin, TxDOT implemented ramp meters at three ramps along a 2.6-mile segment of northbound I-35 for operation during the A.M. peak period. Metering resulted in an increased vehicle throughput of 7.9 percent and an increased average peak period mainline speed of 60 percent through the section. The meters were removed after the reconstruction of I-35 added sufficient capacity to this freeway section. An evaluation performed for MDOT in Detroit determined that ramp metering increased speeds on I-94 by about 8 percent. At the same time, the typical peak hour volume increased to 6,400 vehicles per hour (vph) from an average of 5,600 vph before metering. By reducing merging interference, ramp metering has allowed traffic volumes to approach theoretical capacity. In addition, the total number of accidents was down 71 percent.

The Minneapolis/St. Paul ramp metering system is composed of several systems and subsystems that have been implemented over a 20-year period by MnDOT. A recent study shows that after 14 years of metering operation on I-35E, average peak hour speeds remain 16 percent higher than before metering while peak period volume increased 25 percent over the same period. The average number of peak-period accidents decreased 24 percent and the peak-period accident rate decreased 38 percent. In addition to thirty-nine ramp meters, the system on I-35W includes closed-circuit television, variable message signs, and 380 vehicle detectors. An evaluation of this project after 10 years of service showed that average peak-period freeway speeds increased from 34 to 46 mph. Also, average peak period throughout increased by 32 percent, the average number of peak-period accidents declined 27 percent and the peak-period accident rate declined 38 percent.

The first ramp meters in the Northwest U.S. were installed along a 6-mile section of I-5 in Portland in January 1981. Prior to ramp metering, this section commonly experienced platoons of vehicles merging onto the freeway and congesting traffic. The northbound P.M. peak hour average speed was 16 mph. Fourteen months after ramp meter installation, the average speed for the same time period was 41 mph. In September 1981, Washington DOT implemented metering on I-5 north of downtown Seattle. By 1989, the system was controlling seventeen southbound ramps during the A.M. period and five northbound ramps during the P.M. period. Between 1981 and 1987, mainline volumes increased by over 86 percent for northbound traffic and 62 percent for southbound traffic. Before metering, the travel time on a specific 6.9-mile course took 22 minutes. After metering was installed, the same course took 11.5 minutes, even with the higher volume. Over the same period, the accident rate decreased by 39 percent.

Operational experience has shown that the ramp metering system installed should not only adequately solve the operational problem, but it should also provide the operational features and be well maintained so that the user public will support the system over an extended period. Simplicity of design may be cheaper in the short run, but the public may not like its simple operation and begin ignoring the ramp meters to a point where the meters lose their credibility and efficiency.

Butorac (Ref 4) has identified the following advantages of ramp metering:

1) provides reasonably predictable freeway operation through the regulation of vehicular inputs;
2) reduces the congestion and driver workload at merge points by distributing traffic evenly into the traffic stream;
3) increases mainline capacity and speeds by reducing the potential occurrence of bottlenecks and/or accidents;
4) diverts local trips from the freeway, thereby maintaining the functional classification design and operating policies established by the American Association of State Highway and Transportation Officials (Ref 5);
5) improves interchange operations through the regulation of freeway-to-freeway connector ramps;

6) motivates drivers to convert to high-occupancy vehicles where preferential lane assignments are available;
7) provides incident management capabilities for transportation management centers and freeway managers; and
8) and provides an economical service to the public by protecting the capital investments in freeways by attempting to maintain the flow on these facilities at or near capacity rates and delaying more costly improvements or new roadways.

Ramp metering can produce many benefits; however, implementing this freeway management technique can result in the following disadvantages:

1) creates potential queue spillbacks into the upstream local streets and interchange terminals, service roads, or freeway facilities under high demand volumes or variable arrival patterns;
2) leads to possible equity issues between motorists who are and who are not metered in the urban and suburban areas, respectively;
3) diverts traffic onto the local street system, which can create additional congestion within business districts and neighborhoods; and
4) creates the possibility of delay for motorists at metered on-ramps and freeway connector ramps.

The operational features of single-lane and multiple-lane ramp meters reveal the greatest difference between the two freeway management system design strategies. The single-lane ramp meter cycles at the specified metering rate by either a red-green-red or red-green-yellow-red display sequence when vehicles are present. Most states allow one vehicle to proceed during each green signal display; however, some states have been forced to allow multiple vehicles to be released to accommodate high-demand volumes at an on-ramp location. In general, most states will operate only single-lane ramp meters only up to a maximum discharge rate of 900 vehicles per hour, which represents a 4-second headway between successive vehicles. Agencies have found that headways of less than 4 seconds do not effectively bring vehicles to a complete stop. This situation can create enforcement problems because motorists continually move through the ramp meter.

The multiple-lane ramp meter design strategies differ significantly, such that vehicles in each lane can be either released simultaneously or evenly alternated between lanes. The existence of a second lane allows multiple-lane ramp meters to meter traffic up to approximately 1,800 vehicles per hour while maintaining 4-second or greater headways in each lane. In addition, priority phasing can be given to preferential lanes at a ramp meter. Multiple-lane ramp meter configurations allow agencies to provide preferential lanes to carpools, vanpools, and transit vehicles. These capabilities give multiple-lane ramp meters a significant advantage over single-lane ramp meters in operational flexibility. This operational flexibility is further demonstrated by the lack of excessive queue problems.

The two-ramp-meter design strategies have contrasting operational and traffic control capabilities for dealing with excessive queues. Single-lane ramp meters can effectively meter traffic only up to approximately 900 vehicles per hour and excessive queues can only be cleared through the discontinuation of metering. In contrast, multiple-lane ramp meters can increase the discharge rate up to nearly the saturation flow rate of the on-ramp to clear queued vehicles. This operational flexibility allows multiple-lane ramp meters to continuously regulate and evenly distribute vehicles into the freeway traffic stream, whereas the single-lane design strategy allows a large platoon of traffic to enter the traffic stream. It should be noted that the multiple-lane ramp meter design strategy can accommodate approximately 100 to 130 percent more vehicles within the queue reservoir than the single-lane ramp meter strategy. Multiple-lane ramps also tend to provide a better self-enforcement environment when compared to single-lane configurations (a result of motorists traveling next to one another in the multiple-lane configuration).

Table 2.1 shows the differences between traditional single-lane ramp meters and multiple-lane ramp meters in terms of geometric, traffic control, and operational characteristics of the two design strategies. As shown in Table 2.1, the multiple-lane ramp meter design strategies provide significant operational flexibility over the traditional single-lane ramp meter configuration.

Table 2.1 Ramp Meter Design Strategies Comparative Analysis Summary

	Single-Lane Ramp Meters	Multiple-Lane Ramp Meters
Geometric Elements	• Can be readily designed and constructed on traditional diamond and parclo-type interchanges.	• Requires approximately 24 to 26 feet of pavement within the queue storage reservoir. An absolute minimum of 22 feet should be maintained.
Traffic Control Elements	• Simple control structure.	• Requires additional detection and more advance controllers.
Operational Elements	• Cannot effectively meter demand volumes exceeding 900 vehicles per hour or highly variable arrival patterns with demand volumes exceeding 750 vehicles per hour. • Excessive queues cause lapses in metering or surface street congestion. • Preferential lane priority for carpool, vanpool, and/or transit cannot be provided.	• Capable of metering demand volumes up to approximately 1,800 vehicles per hour. • Wider range of metering rates allows for effective queue management. • Preferential lane priority for carpool, vanpools, and/or transit can be provided.

A proposed set of application guidelines for both ramp meter configurations are listed below:

1) Ramp meters should only be deployed at locations that provide sufficient area for traffic control devices, vehicular storage, and vehicular acceleration to freeway speeds.
2) Proposed ramp metering locations should provide an adequate queue storage reservoir for existing and future ramp conditions (i.e., demand volumes and arrival patterns). Ramps that do not provide adequate queue storage reservoirs should maintain sufficient queue management traffic control capabilities.
3) Single-lane ramp meters should not be used in locations where the demand volumes are expected to exceed approximately 900 vehicles per hour even after traffic is redistributed between on-ramps within a specific section of freeway that will be metered. In addition, single-lane ramp meters should not be used on locations that maintain on-ramp demand volumes in excess of 750 vehicles per hour and highly variable arrival patterns.
4) Multiple-lane ramp meters should provide the proper pavement widths and lateral clearances to accommodate two lanes of traffic within the queue storage reservoir. In addition, preferential lanes should provide proper access to avoid queue spillbacks (i.e., mixed-traffic queues should not block access to the preferential lane).
5) Grades in the vicinity of the ramp meter stop-bar should be minimized to avoid vehicles losing traction within both the queue storage reservoir and acceleration areas of the on-ramp.

Despite some public opposition, freeway-to-freeway ramp (connector) metering is asserting itself as a viable tool in alleviating freeway congestion. Reports have indicated that the implementation of surface-street-to-freeway ramp metering needs to be accompanied by connector metering to provide appreciable benefits. The following outlines the potential benefits of connector metering (Ref 6):

1) Connector metering provides for displacement of queuing from the mainline to connectors, providing a consistent, controlled traffic situation with better safety characteristics.

2) Connector metering in combination with ramp metering could provide additional support to incident management strategies in avoiding an operational breakdown of the freeway created by an accident.
3) Connector metering improves flow through the bottleneck area on the mainline, with attendant increases in traffic volume.
4) Connector metering will improve the efficiency of on-ramp entrance metering upstream of the freeway-to-freeway interchange.
5) Connector metering improves equity among drivers along the corridor.
6) Connector metering provides diversion of connector traffic to alternate routes, providing better utilization of the freeway corridor.

However, possible disadvantages resulting from freeway-to-freeway ramp metering include:

1) Regulating traffic on an interchange connector will result in queues that may extend into the freeway mainline traffic and interrupt operations.
2) Depending upon the location of the connector meters with respect to surface street meters, it is possible for a motorist to incur metering more than once for a single trip.
3) Existing interchange configurations are not conducive to implementing metering and may require upgrading or geometric changes to provide the necessary storage requirements for queues.
4) Probably one of the largest problems associated with any metering project is in convincing the commuting public that the systems do provide a measurable benefit. A successful project requires that the attitude of the public and of public officials be assessed and properly accounted for in presenting plans that include connector metering. Many projects have reported a barrage of complaints when initially implementing metering, but find that these soon dissipate when time-saving benefits from the system are realized.

Connector metering is a cost-effective and proven resource for relief of recurrent congestion. As a logical extension of ramp metering, it provides operational flexibility for freeway corridors and contributes to the large number of benefits that are found in freeway management strategies. Connector metering provides for a smoother dispersion of vehicles on interchange ramps, and in conjunction with ramp metering, can be used to blunt sharp peak-hour arrival trends. Connector metering also provides incentives for drivers to participate in other freeway management strategies, such as carpooling, busing, and transit. Furthermore, connector metering provides increased equity along the freeway corridor and improves the efficiency of metering rates at other ramp locations. Some additional user benefits from connector metering are in a decrease in accidents along connector ramps and at merge areas, a decrease in fuel consumption resulting in a reduction of emission pollutants, an increase of average freeway speeds during peak periods, and a shortening of the peak-period duration.

The suggested policy on freeway-to-freeway ramp metering is to install meters on freeway-to-freeway ramps where system performance and efficiency will be improved. Suggested guidelines for freeway-to-freeway ramp metering include the following (Ref 7):

1) Consider and implement freeway-to-freeway ramp metering where recurring congestion is a problem or where route diversion should be encouraged. Installation of the meters should be accompanied by a marketing and publicity campaign.
2) Consider route diversion only where suitable alternative routes exist to avoid diverting drivers through residential neighborhoods. Normally, route diversion is not the intention of freeway-to-freeway ramp metering. Instead, freeway-to-freeway ramp metering should be installed to improve the mainline flow and on-ramp merge, or to help multiple ramps merge into one ramp. If the intent of the metering is route diversion, then consider trailblazers or appropriate signing to educate drivers on preferred alternative routes.
3) Avoid metering vehicles twice within a short distance. If ramp meters are installed within 5 km (3 miles) upstream of a freeway-to-freeway ramp, the freeway-to-freeway ramp should not be metered.
4) Avoid metering single-lane, freeway-to-freeway ramps that feed traffic into an add lane. Because the maximum single-lane metering rate is usually 900 vph (although it can be increased by allowing two vehicles per green cycle), an add lane with a capacity of over 2,000 vph would be underutilized.

5) Do not install meters on a freeway-to-freeway ramp unless analysis ensures that the mainline flow will be improved so that people using the freeway-to-freeway ramp are rewarded for waiting in line at a metering installation.
6) Install meters on freeway-to-freeway ramps where two or more ramps merge before feeding onto the mainline and where congestion on the ramps occurs regularly (four or more times a week during the peak period).
7) If traffic queues that impede mainline traffic develop on the upstream mainline because of freeway-to-freeway ramp metering, increase the metering rate to minimize the queues on the upstream mainline, or provide additional storage capacity.
8) Monitor and control freeway-to-freeway ramp meters by the appropriate traffic management center.
9) Whenever possible, install meters on roadways that are level or have a slight downgrade, so as to ensure that heavy vehicles can easily accelerate. Also, install meters where the sight distance is such as to allow drivers approaching the metering to see the queue in time to safely stop.

HOV BYPASS LANES

Bypass lanes for high-occupancy vehicles at metered entrance ramps represent a relatively low-cost priority treatment that can provide travel-time savings to HOVs. In some cases the amount of time saved on an HOV bypass of a metered ramp is sufficient to induce increased use of carpooling and transit; more frequently it is a small incentive that can be combined with other measures to make high-occupancy travel more attractive.

A paper by Lomax (Ref 8) focuses on the current practice in geometric design of metered entrances and HOV bypass lanes. Most of the ramp meters and HOV bypass lanes that have been constructed to date are the result of retrofit design policies that made the most efficient use of space and funding. Where there are design standards or guidelines, it is frequently difficult to provide desirable design dimensions for freeway ramps that were not designed for the different operating characteristics of a metered entrance ramp. In the paper, therefore, both desirable and retrofit design practices are presented to illustrate both the application of typical design standards and what has been successfully implemented by local transportation agencies. Whereas desirable standards are important to the design process, it is also important to note those designs that appear to work well.

Several states have specific documents related to the design of ramp metering, HOV bypass lanes, or both. The major items specified in these documents include the following:

- Width of the entrance-ramp lane and shoulders.
- Length of the entrance ramp and the merge area to the freeway lanes.
- Signalization.
- Signing and marking.
- Queue storage considerations.
- Separation of HOV and general ramp traffic.
- Enforcement of HOV restrictions.

Some designs work well because drivers are familiar with them and understand what is needed to overcome the inadequacies. A more detailed investigation of the compromises inherent in the implementation of ramp meters and HOV bypasses is needed to identify those approaches that work consistently well and those that, if installed, need more driver information to operate efficiently. That investigation should include such factors as traffic volume, number of lanes, ramp length, merge area, queue storage, signing, signalization and marking, and ramp grade.

LANE USE RESTRICTIONS

With the increased expansion of highways, questions have arisen as to the proper operational strategy of those facilities. One strategy gaining support is to restrict large vehicles from one or more lanes, usually temporarily, for one or more of the following reasons:

1) To improve highway operations,
2) To reduce accidents,
3) To provide for more even pavement wear and
4) To ensure better operation and safety through construction zones.

Zavoina (Ref 9) analyzed the operational effects of a truck restriction on I-20 near Fort Worth, Texas. Vehicle distributions according to classification, vehicle speeds, and time gaps between vehicles were examined to evaluate the operational effectiveness of this left-lane truck restriction. The restriction succeeded in its purpose, with compliance rates ranging between 62 and 76 percent without enforcement. Few trucks were present in the left lanes of the roadway before the restriction. After the restriction; only 3 percent of all trucks remained in the left lanes. At the reported study site, the percentages of trucks significantly increased in both the center and right lanes of each direction. This redistribution of trucks did not cause any change of practical significance in the distribution of cars.

The examination of speeds resulted in statistically significant changes in the speeds of trucks relative to cars from before to after the restriction, however, the changes could not be attributed to the truck restriction. Speed changes from before to after the restriction were also investigated by comparing the speed differentials in each lane. This speed differential measure was defined as the absolute value of the difference in the vehicle speeds within each pair of consecutive vehicles. Significant reductions in average speed differentials were found, but a coincident increase in volume, which also occurred during the same period, is the most probable cause of this result.

The final test, which explored the likelihood of trucks bearing down on cars, examined the proportion of instances in which trucks followed cars with small time gaps. Only two of twenty-four tests were statistically significant, indicating that the greater concentration of trucks in the right lanes did not result in an increase in this event.

Implementation of truck restrictions, such as the lane restrictions studied, theoretically has the potential to improve the capacity and safety of the roadways. The lack of evidence from the research to support strong conclusions in these areas has two important implications. The first implication is the requirement that the results reported in the paper be applied only to similar roadways, i.e., rural, low-volume facilities with relatively little truck traffic. The second implication is the need for further research to investigate whether these results can be extended to higher volume roadways or to roadways with larger truck percentages.

RESPONSE TO MAJOR INCIDENTS

Travel demands for trucks and automobiles continue to increase while the rate of expansion of the roadway networks decreases. While the rate of incidents may stay constant or, in some cases, even fall, the number of incidents and their impact on mobility and safety will multiply with the increased demands, particularly in urban areas. The safety of the roadway is related to incidents and dependent on their frequency and on the length of time that they affect traffic operations. There exists today the facilities, equipment, and knowledge to improve incident management. Incident management is a complex problem because it involves many different agencies. Incidents cannot be easily predicted (Ref 10). Likewise, the location and severity of incidents cannot be known until information is transmitted from the incident scene. However, there are better means of communication to employ quicker procedures for clearing a roadway and a more effective means of controlling traffic approaching an incident. What is needed is a plan to improve the overall response to incidents and commitments on the part of the agencies and the persons involved in incident management to implement the plan. However, it is not realistic to expect that one plan will apply equally well to every area.

Urban freeways and highways are highly susceptible to events that reduce roadway capacity and increase travel delays and operating costs for motorists. Studies have determined that random events, such as accidents and vehicle breakdowns, cause 50% or more of the traffic congestion on streets and highways. Incident management, especially for incidents involving large trucks with potentially hazardous cargo, requires coordinated and pre-planned procedures that make use of all available human and electronic/mechanical resources. These procedures include: 1) detecting the incident; 2) identifying the extent of the incident (the number and type of vehicles involved, the number of lanes affected, the severity of the incident, the time of closure, etc.); 3) identifying the response requirements (which agencies need to respond, the type of equipment needed, the personnel and materials needed to manage traffic, etc.); and 4) providing the appropriate aid to the motorists involved and clearing the incident area as quickly as possible. By reducing the amount of time that incidents affect traffic, the provision of guidelines and the establishment of incident response plans should minimize congestion, reduce traffic delays and fuel consumption, and enhance the overall safety of operations.

An incident inventory analysis was initiated to determine:

1) How often a major freeway incident can be expected to occur as a function of traffic and geometric variables;
2) The basic characteristics of major incidents in terms of their frequency by time of day, severity, type, and duration; and
3) If and how the duration of incidents differs as a function of the incident characteristics.

Incident management and response requirements were developed to deal with small, midsize, and large urban areas. Specifically, components of incident duration, detection, verification, and response capabilities were identified. The application of advanced technologies was also investigated to identify any potential ties to incident management and response. Some of the technologies identified include: Geographic Information Systems, Dynamic Route Guidance, Total Stations, Automatic Vehicle Identification, Highway Advisory Radio, Closed Circuit Television, and Changeable Message Signs.

Guidelines for incident response by agencies were developed to:

1) Establish a multi-agency consensus for incident response planning,
2) Identify a common incident classification,
3) Establish interagency cooperation agreements, and
4) Develop interagency communication protocols.

Also identified were agency incident preparations for on-site response, site specific planning, levels of response, and training criteria. Additional response guidelines were developed for maintaining traffic flow, removing disabled vehicles, dealing with hazardous materials, and reporting incident criteria for evaluation purposes.

The application of advanced technologies for incident response offers significant improvement to the existing system used to detect, verify, respond to, and clear major freeway incidents. Inclusion of these is vital to transportation agencies dealing with incidents.

The guidelines for agency response presented in this report outline the criteria necessary for incident management within Texas. These guidelines are sometimes practical recommendations (i.e., maximizing traffic flow past the incident, use of emergency vehicle flashing lights, removal of vehicles, dealing with hazardous materials, etc.). However, specific criteria dealing with incident planning, classification structure, cooperative agreements, and communication protocols were also identified. Two of the most important results identified in this study were (1) the agency reporting and documentation of incident data and (2) the pre-planning incident activities, especially that of diversion strategies.

Evidence from case study locations suggests that the development of alternative route plans is the incident response planning activity of greatest interest to transportation-related agencies. Agencies should prioritize potential incident locations based on likelihood and severity of occurrence, and initiate efforts to establish feasible alternative route plans early on in the incident response planning process. In some instances, more than one alternative route may need to be identified to accommodate the volume of freeway traffic that would need to be diverted.

As a result of the case study analyses, it appears that two types of manuals may be needed to completely document incident response activities in a region: (1) a field manual to be carried by law enforcement officers that identifies specific actions (telephone numbers, ramp closures, alternative routes, etc.) to be enacted based on the location and severity of the incident, and (2) an office manual that documents the interaction between various agencies, the various traffic management components involved, and how they should be used.

REDUCED LANE AND SHOULDER WIDTHS

Yagar and Hui (Ref 11) discuss the pros and cons of reducing lane and shoulder widths to obtain an extra travel lane with emphasis on the effects on the overall freeway system. They also describe how an increased capacity at an upstream location can overload a downstream bottleneck and cause flow breakdown.

Determining where, or even whether, to restripe sections to gain capacity and strategically relieve bottlenecks is far more complicated than estimating the local capacity gain. Removal of a bottleneck may shift the bottleneck downstream or uncover another hidden bottleneck that could defeat the purpose of restriping. In some cases, bottleneck removal may actually provide net disadvantages, somewhat akin to canceling a naturally occurring incidence of mainline metering. A systems approach is required for evaluating capacity changes on freeway corridors, where major parallel routes may or may not exist. Even when there is no alternate route, a bottleneck on a major urban freeway affects both upstream and downstream sections. Removal of that bottleneck will usually cause another bottleneck elsewhere on the freeway. An analysis of the freeway system should be performed to identify the potential impact of relieving a specific bottleneck so that the negative system effects are minimized. Hidden bottlenecks and physical limitations on capacity complicate the evaluation of alternative improvement schemes.

All bottlenecks are not necessarily harmful to a system; some bottlenecks behave as regulators controlling the flow downstream. An important phenomenon of freeway flow is the hysteresis effect related to flow breakdown. When demand exceeds free-flow capacity, flow breaks down to an even lower capacity governed by queue discharge headways that are typically 10 to 15 percent greater than reasonably sustainable free-flow headways. This results in a corresponding capacity reduction of 10 to 15 percent. The extent of capacity reduction caused by flow breakdown varies with geometric conditions and may even vary from day to day. Post-breakdown queue discharge flow rates of 6 to 12 percent less than pre-breakdown capacity were observed in Toronto. Bottlenecks should be carefully evaluated in a systems context to ensure that a desirable bottleneck is not removed.

When there are alternative routes, drivers will tend to seek paths that minimize their travel costs. When conditions vary from day to day, some drivers will reroute on the basis of real-time information, experience on the network, or both. Ultimately, those drivers who are able to reroute will allocate themselves so that an equilibrium of delay exists between the alternative routes. In other words, as the travel time on one route increases, some drivers will take the opportunity to shift to another route, producing a dynamic balance of travel times on the system.

BOTTLENECK REMOVAL FEASIBILITY

Congestion on urban freeways impacts safety, motorist delay, air quality, and energy consumption. In areas where travel demand far exceeds capacity, some level of congestion will be inevitable. However, where imbalances in the freeway system exist, bottlenecks restrict the use of available capacity. Valuable capacity can be recaptured, congestion reduced, and impacts diminished if these bottlenecks can be removed. Walters (Ref 12) defines bottlenecks, discusses methodologies for identifying and determining the cause(s) of a bottleneck, suggests appropriate ways to alter geometrics to diminish the impacts of a bottleneck, and provides a methodology to estimate the benefits to be expected from implementing a bottleneck improvement.

A bottleneck in a freeway system causes the available capacity to be under-utilized, with congestion (stored demand) upstream and free flow conditions at a volume reflecting the bottleneck capacity downstream. The bottleneck may limit flow downstream to less than the available freeway capacity. In this era of maximizing the efficiency of existing traffic systems, bottlenecks need to be understood and, where appropriate, eliminated. Often, the constriction can be removed through a relatively low-cost improvement to a short section of the freeway within existing right-of-way. Such improvements sometimes involve nothing more than converting a shoulder to a driving lane with slight narrowing of main lanes from 12 feet to 11 feet.

Not every site with recurrent congestion is caused by a bottleneck. Demand on some freeways is simply over capacity and unstable flows frequently break down into stop-and-go conditions. This report will: 1) define bottlenecks, 2) discuss methodologies for identifying a bottleneck and discovering its causes (there may be more than one, and they can be deceptive), 3) suggest appropriate ways to alter geometrics to better fit the demand, and 4) provide a methodology to estimate benefits expected from bottleneck removals, as a means of determining the feasibility and priority of a proposed project. Examples of implemented projects where before-and-after data have been collected are included, along with the lessons learned.

A bottleneck is defined, for the purposes of this report, as a short section of freeway for which the demand, in one or more lanes, exceeds capacity, resulting in congestion upstream and free flow conditions downstream. There are two reasons bottlenecks occur in freeway systems. First, design hour volumes for ramps are not well predicted by simple using K and D factors provided for freeway design. The Highway Design Manual (Ref 13) suggests use of the formula "DHV = 2 x K x D" to convert twenty-four hour volume projections for ramps into design hour volumes. In reality, actual ramp volumes have little correlation to the adjacent freeway K and D values and indicate that local land use patterns are of much greater significance in peak hours. Thus, designing a good interchange to meet future peak-hour demands is difficult.

The second reason bottlenecks occur is that facilities are designed for volumes expected in the design year, perhaps as much as 25 years in the future. Land use changes may not be easily predicted that far into the future so even the 24-hour projections may eventually prove to be highly inaccurate. It should therefore be no surprise that bottlenecks develop and every attempt should be made to fix them when they do. Obvious candidates for inspection of possible bottlenecks are areas of recurrent congestion; these areas may be discovered via traffic reports, complaints to the districts, or personal contact and experience.

Five types of data collection are recommended at a suspected bottleneck site:

1) Traffic volume counts by 15-minute periods.
2) Travel time runs throughout the congested corridor on 15-minute headways.
3) Videotape of the operation at the bottleneck.
4) Drive-through video on each approach through the congestion.
5) Origin-destination data if a weave is involved.

Typical low cost improvements include:

1) Using a short section of shoulder as an additional lane.
2) Restriping merge or diverge areas to better serve demand.
3) Reducing lane widths to add a lane.
4) Modifying weaving areas.
5) Metering or closing entrance ramps.

Many of these options require more pavement to some degree. Is there an inside shoulder that would create a usable traffic lane for a short section of freeway? If there are bridges, are they wide enough to accommodate the extra lane while allowing adequate clearance to barriers (2 feet) and an outside shoulder? If not, are they short enough that loss of a shoulder as a breakdown lane would not be critical (less than 500 feet)? If changes to an entrance or exit ramp or weaving area are considered, will adjusting the position of ramp gores cause geometric problems that must be resolved? Are vertical clearance issues, gradematching, and sight-distance problems created? If a shoulder is considered for removal, is there right-of-way to allow adding one back for part of the length of the project?

The issue of shoulder removal has safety implications. Although loss of a breakdown lane can sometimes result in a disabled vehicle blocking a travel lane, which is obviously hazardous, the alternative of allowing a bottleneck to continue, causing recurrent stop-and-go congestion on a freeway, is perhaps more hazardous. Research by Urbanik (Ref 9) suggests that shoulder conversion to remove bottlenecks has an overall positive effect on safety. There remains the possibility that congestion could develop again and that the loss of the shoulder would create a condition worse than before. This lends greater emphasis to the need for certainty that the proposed improvement is actually elimination of a bottleneck and not simply a capacity improvement, which is likely to induce more overall freeway traffic and break down again.

Bottleneck removal involves careful detective work, and time spent on data collection and analysis will pay off handsomely; inadequate investigation of the specific causes and potential system effects can lessen the intended benefits. However, this type of improvement generally has an extremely high benefit/cost ratio. Many improvements can be made with simple restriping, while others may require more major construction, but which can still be funded for a fraction of normal capacity improvements. Bottleneck removal is analogous to intersection improvements in an arterial system; money spent on adding extra turning lanes for a short distance in an arterial system may preclude the need for widening an entire thoroughfare.

The following summarizes the key points to bottleneck removal:

1) Traffic volumes alone will not detect (but may suggest) locations of bottlenecks; vehicle speeds, local traffic patterns, and field observations are needed to detect the existence and the causes of freeway bottlenecks.
2) The amount of congestion on different approaches at freeway interchanges can be very imbalanced; distributing the capacity to reflect the demand can significantly reduce the overall congestion in the system.
3) Improvements such as restriping lanes, using shoulders, and modifying weaving areas produce primary benefits of reduced congestion and improved safety, as

well as secondary benefits in emission reduction, vehicle operating costs, and congestion on alternate routes.

4) These benefits can be obtained, not by adding freeway capacity, but by *recapturing design capacity* within the freeway system; this becomes an increasingly important distinction as regular capacity improvements are becoming more difficult to justify, environmentally and politically.
5) Additional checks must confirm that implementation of a bottleneck improvement will not simply move the congestion to another location (which may have further safety implications).

SUMMARY

Bottleneck reduction, incident management, and congestion management are important operational concepts. Implementation of measures ranging from HOV lanes to reduced lane widths have potential, but use of all such measures could be simplified if designs incorporate flexibility. The preceding review of congestion mitigation techniques was provided to highlight the types of activities for which flexible design measures should be developed.

CHAPTER 3 OPERATIONAL FLEXIBILITY FOR CONTROLLED ACCESS FACILITIES

The term "incident" is commonly used to describe many kinds of traffic stream interruptions. Incidents include accidents involving collisions between vehicles or vehicles and roadside objects, disabled vehicles, objects such as vehicle parts or lost cargo or literally any unplanned traffic flow disruption. The FHWA data showed that around 60 percent of all urban freeway congestion delay in the United States is caused by incidents (Ref 15). Particularly on controlled access facilities, incidents cost travelers significant time delays, which equal large economic costs, and often cause secondary accidents.

Due to continual traffic growth, major metropolitan areas have initiated various incident management programs. Such programs include freeway surveillance systems, incident response teams, law enforcement officers, motorist assistance patrols, and other means to detect, respond, and clear incidents (Ref 16). The goal of these programs is to minimize incident effect, and to quickly restore the freeway traffic to normal operation. Experience indicates that such programs are very effective. Modern traffic control centers identify incidents very fast, and with high-resolution video cameras, can determine what kind of emergency services are needed. Usually, the incident identification and verification time does not exceed two minutes. The next step is for an emergency team to arrive at the scene, but congested traffic conditions and limited flexibility of controlled facilities, such as urban freeways, makes the response process relatively slow.

Therefore, operational flexibility has a great potential for accident management by reducing the likelihood of accidents, and maybe more significantly, reducing the accident duration thereby reducing traveler delay and associated cost. In order to define potential roles for operational flexibility in accident management, studies of more than 100 accidents were conducted using Houston and San Antonio traffic control center capabilities. Accidents on urban multilane freeways were video recorded, together with general traffic situation on the involved freeway section. The purposes of observations were: (1) to investigate influence of accidents on freeway traffic, (2) to identify problems, and (3) to develop recommendations for minimizing their effect.

DATA COLLECTION

Houston and San Antonio, Texas were selected for data collection because both cities have large freeway networks, high traffic condition variability, and high accident frequency. For data collection, the research team chose video recording using facilities and equipment of the Texas Department of Transportation traffic control centers: TRANSTAR (Houston) and TRANSGUIDE (San Antonio). Both centers use high resolution color video cameras installed atop camera poles. The cameras have 750 lines of horizontal resolution, six shutter speeds, and remote control zoom-focus and iris operations. A standard 2/3 inch 16:1 high power lens equipped with a 1.5 tele-converter and built-in 2X extender were mounted on the video camera poles. Camera focal lengths range from 16 mm to 427 mm and the field of view at 1/2 mile is 20 feet vertical by 30 feet horizontal. Numerous video cameras cover large functions of the major freeways in both cities.

During data collection, when an accident identified, operator focused the remote camera on it and began recording, continuing until normal traffic conditions on the observed freeway section were restored. The gap between the time when an accident occurred and when the operator identified it was usually less than 2 minutes. Four video recorders were installed in each center, allowing simultaneous accident recording on different freeway sections.

All video frames have freeway identification (freeway name and direction), video camera identification (number and location), as well as date (month, day, year) and time (hours, minutes, seconds). Figure 3.1 shows a sample video recording.

Figure 3.1 Sample of Accident Video Recording

In total, more than 100 accidents were collected and analyzed. Each accident description included number of traffic lanes, existence of shoulders and protective barriers, number of vehicles involved, traffic lanes that were blocked and open, reason for lane blockage, duration of blockage, significance of influence on freeway traffic, emergency vehicle arrival, and departure times and approach path. Tables 3.1, 3.2, and 3.3 represent samples of detailed accident descriptions for the accident shown in Figure 3.1.

Table 3.1 General Accident Description

Accident #	San Antonio. Accident # 2
Tape #	4
Day	5/10/99
Camera I.D.	US 281N at the River
Time when recording began:	7:17
Time when recording stoped:	8:22
Number of traffic lanes in one direction:	4
Shoulders:	Median + Outside
Protective barriers:	Median (concrete)+ Outside (metal)
Number of vehicles involved in accident:	1
Traffic lane where accident happened:	2

Table 3.2 Traffic Lane Blockage Description

San Antonio. Accident # 2					
Traffic Lane Blockage					
Lane (s)	Time		Duration, min.	Reason for blockage	Influence on traffic
	From	To			
1,2,3	7:17	8:00	43	tanker truck, police	major
1,2,3,4	8:00	8:01	1	tanker truck, police, tow truck	stop
1,2,3	8:01	8:05	4	tanker truck, police, tow truck	major
1,2	8:05	8:22	17	tanker truck, police, tow truck	major
None	8:22				none

Table 3.3 Emergency Vehicle Arrival, Departure Times, and Approach Path

San Antonio. Accident # 2			
Emergency Vehicles:			
Type	Arriving time	Arrived by	Departure time
Ambulance	7:21	Regular direction main lanes	7:37
Police 1	7:23	Opposite direction main lanes and shoulder	8:21
Tow truck	7:59	Regular direction main lanes	8:21
Police 2	8:11	Regular direction main lanes	8:21

* emergency vehicles – ambulance, police, tow truck, fire truck

Detailed descriptions and photos of each accident are provided in Appendices A and B for Houston and San Antonio, respectively.

DATA ANALYSIS

The following characteristics were selected for analysis:

1. Fraction of accidents occurring by different traffic lanes
2. Fraction of accidents blocking one, two, three or more lanes.
3. Duration of roadway blockage
4. Fraction of cases where all lanes were blocked at some time
5. Duration of influence on traffic
6. Time duration in which emergency vehicles were present
7. Emergency vehicle arrival path

For analysis, the main roadway cross section was divided into right, central, and left sections. A central accident location was determined if drivers could pass around the accident on both the right and left sides. Right and left sections determined as outside and inside parts of roadway cross section correspondingly.

An incident was identified as causing roadway blockage if one or more vehicle(s), stopped in a main traffic lane or on a shoulder, caused a measurable effect on traffic. Blockages included situations in which police officers stopped traffic on some lane(s) during incident clearance efforts. Because the roadway cross section was divided into right, center, and left sections, which could be blocked simultaneously, total blockage time does not equal the sum of the blockage times by roadway sections.

The influence of an incident on traffic was classified as being of minor, medium, or major significance. Minor significance was determined when the accident did not affect through traffic flow (no visual flow speed reduction, no traffic lane blockage, or drivers in the blocked lane could easily merge into the open). Major influence was a significant traffic flow speed reduction. Drivers on the blocked lanes were forced to stop and wait for an appropriate merging situation on neighboring traffic lanes. General traffic conditions significantly deteriorated and the accident created a major bottleneck.

These descriptive terms are applied to each investigated accident in Appendix C. All collected data were analyzed separately for freeways with two and three lanes in one direction, freeways with more than three lanes in one direction, and all freeways combined. Figures 3.2a through 3.15b show graphical representations of the analysis concepts for both cities. More detailed analyses are shown in Appendices D and E for Houston and San Antonio, respectively.

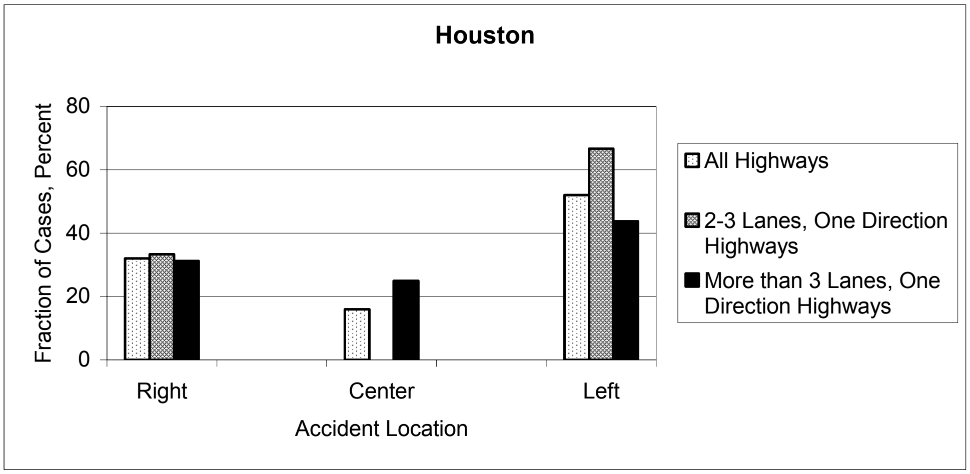

Figure 3.2a Relative Accident Locations within Highway Cross Sections (Houston)

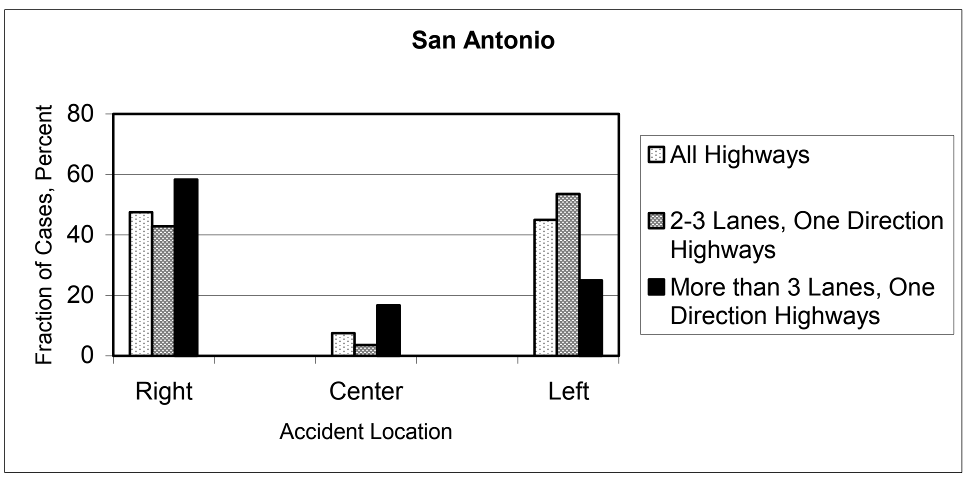

Figure 3.2b Relative Accident Locations within Highway Cross Sections (San Antonio)

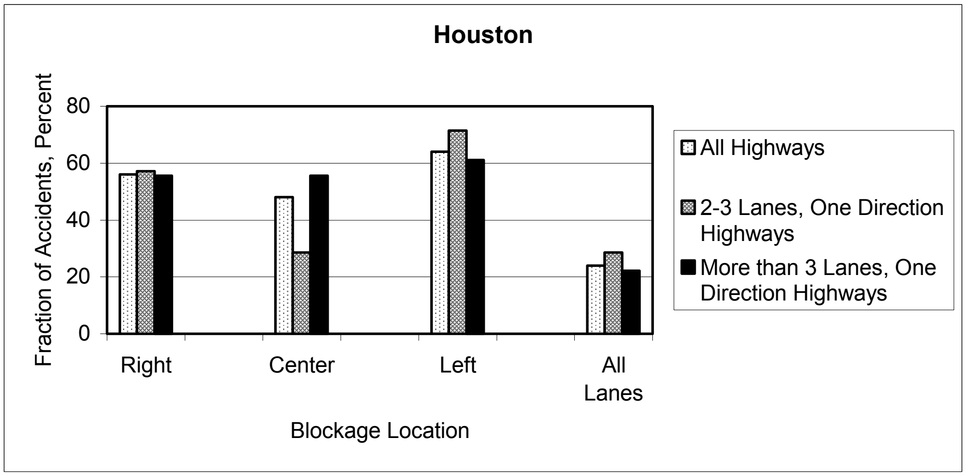

Figure 3.3a Fractions of Accidents versus Cross Section Location Blocked (Houston)

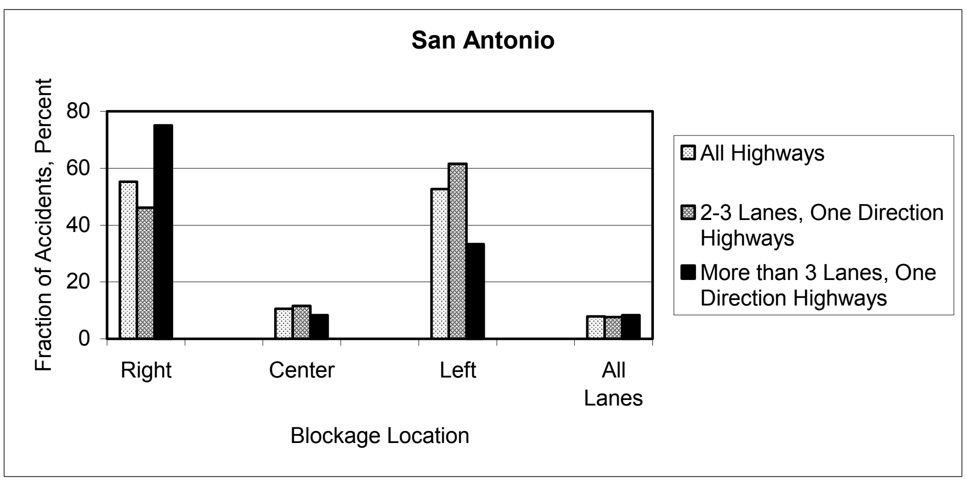

Figure 3.3b Fractions of Accidents versus Cross Section Location Blocked (San Antonio)

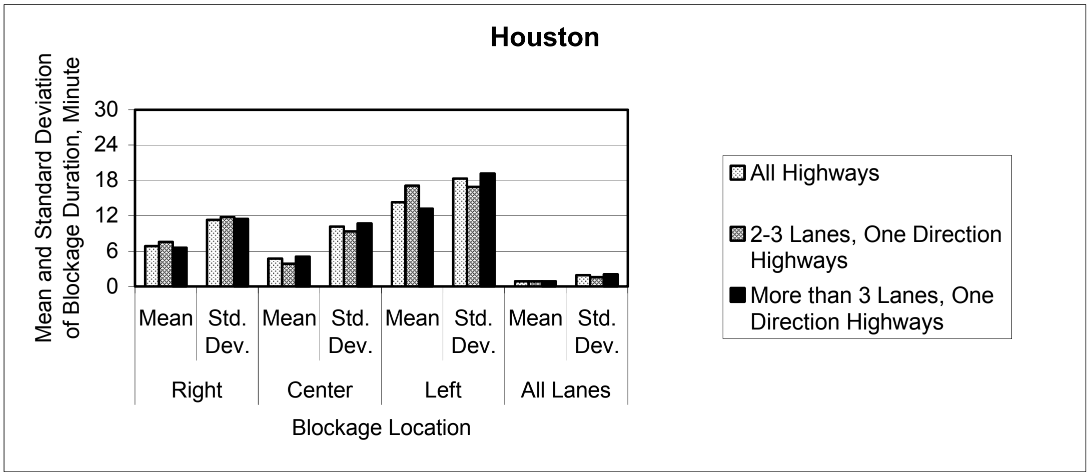

Figure 3.4a Duration of Blockage by Cross Section Location (Houston)

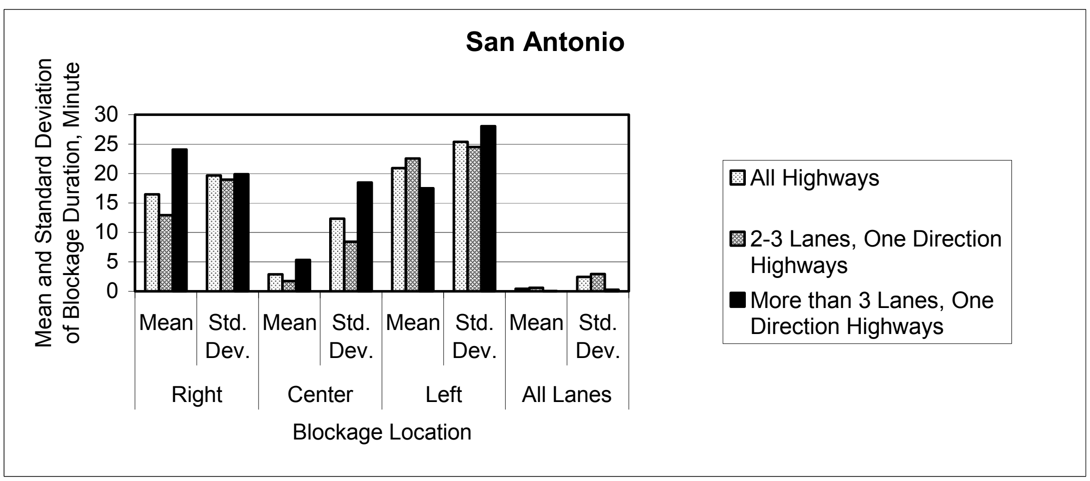

Figure 3.4b Duration of Blockage by Cross Section Location (San Antonio)

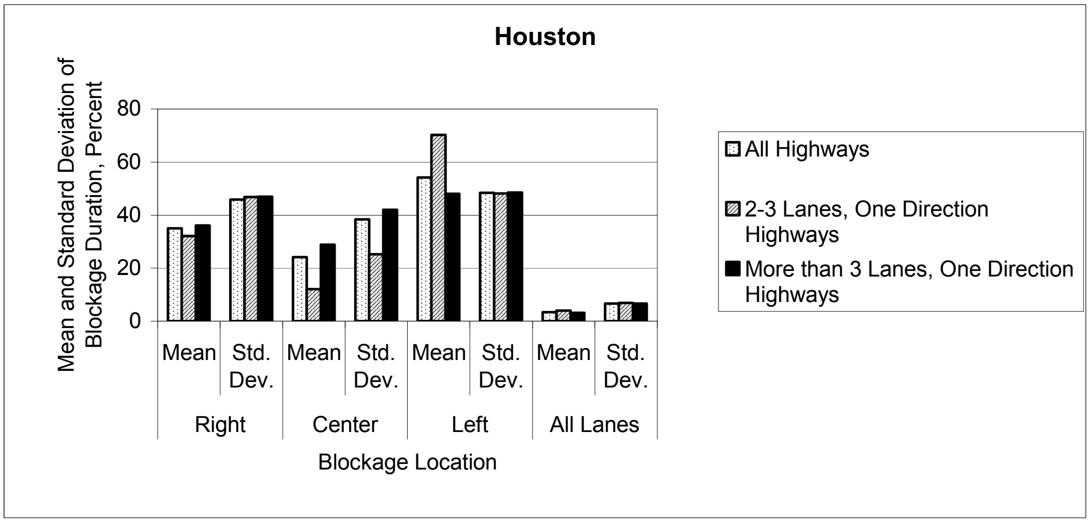

Figure 3.5a Percentage of Total Blockage Duration by Cross Section Location (Houston)

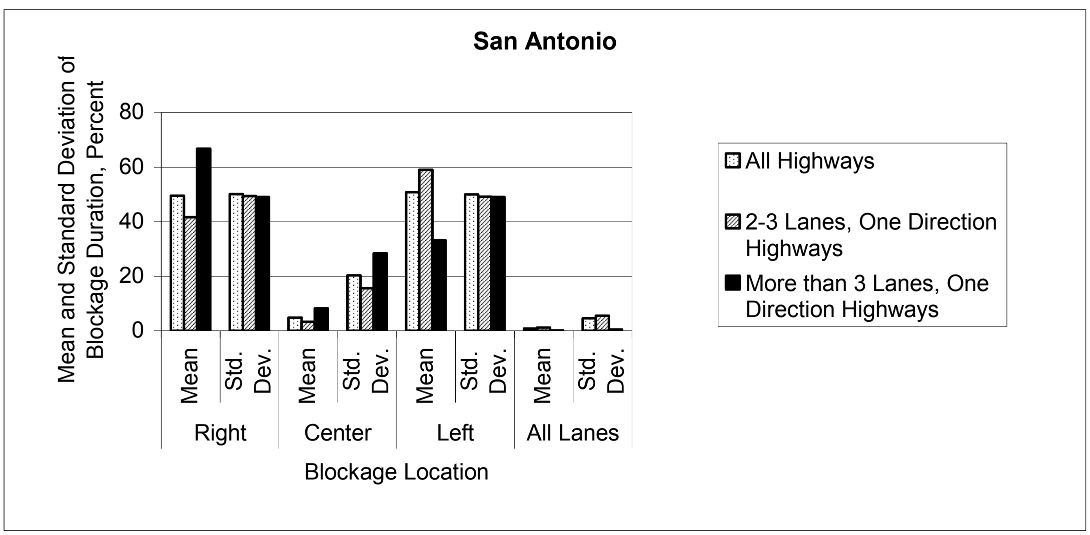

Figure 3.5b Percentage of Total Blockage Duration by Cross Section Location (San Antonio)

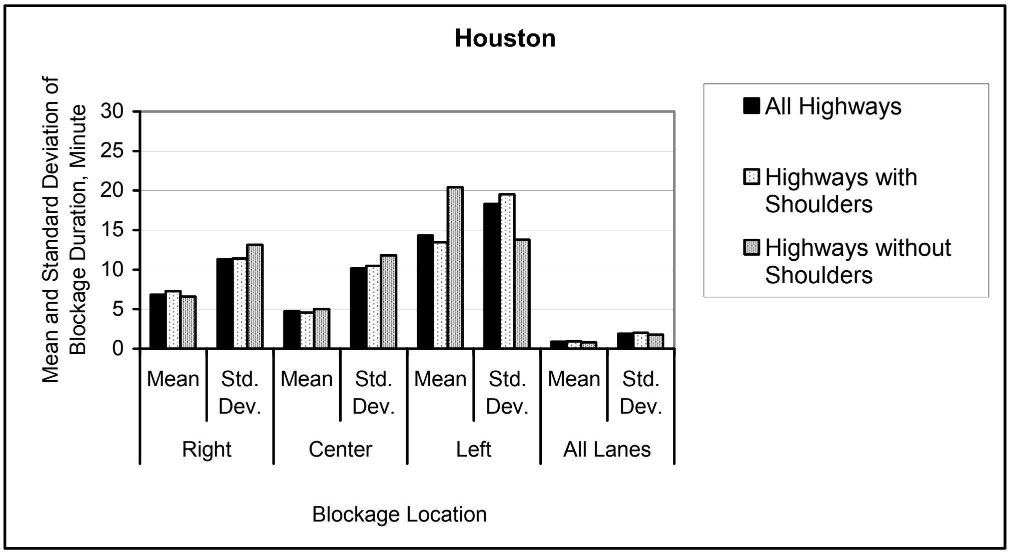

Figure 3.6a Duration of Blockage by Cross Section Location for Freeways with and without Shoulders (Houston)

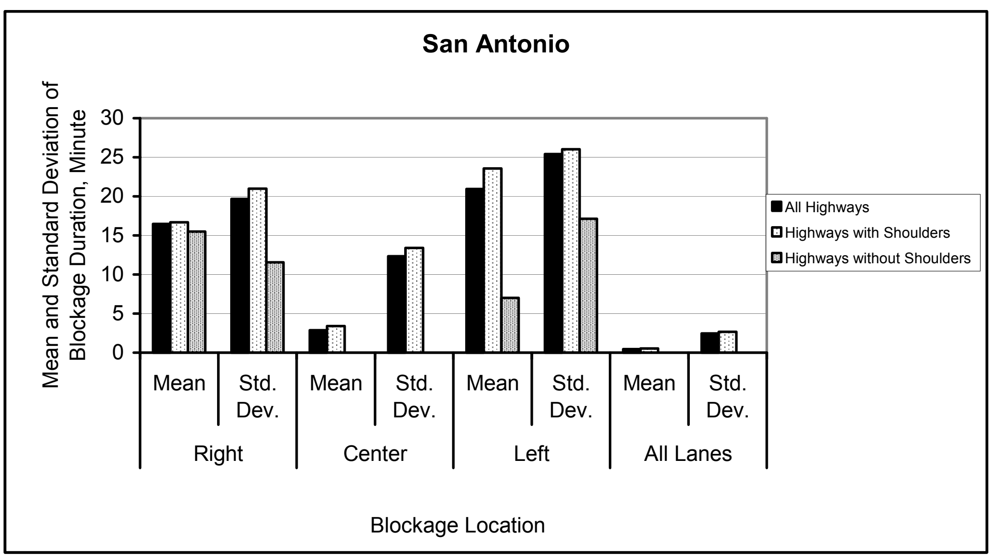

Figure 3.6b Duration of Blockage by Cross Section Location for Freeways with and without Shoulders (San Antonio)

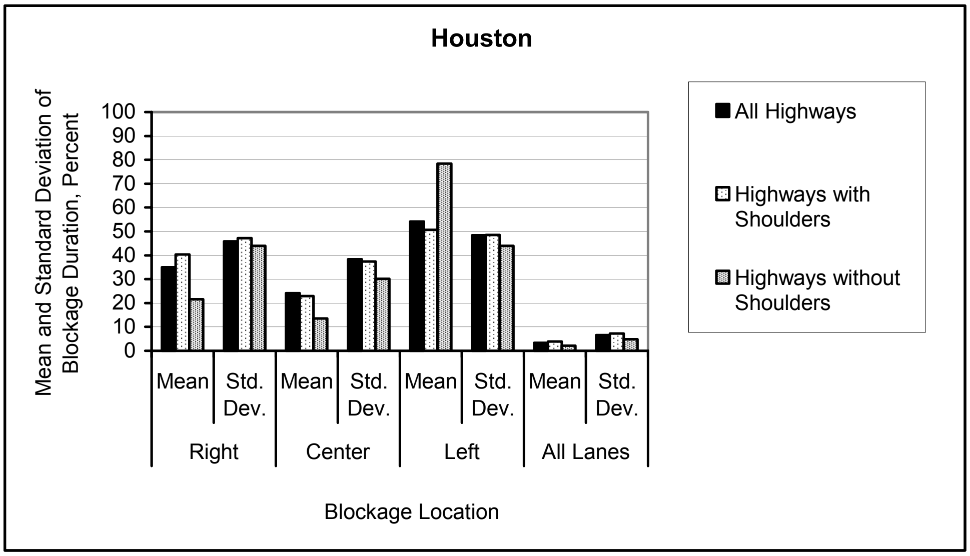

Figure 3.7a Percentage of Total Blockage Duration by Cross Section Location for Freeways with and without Shoulders (Houston)

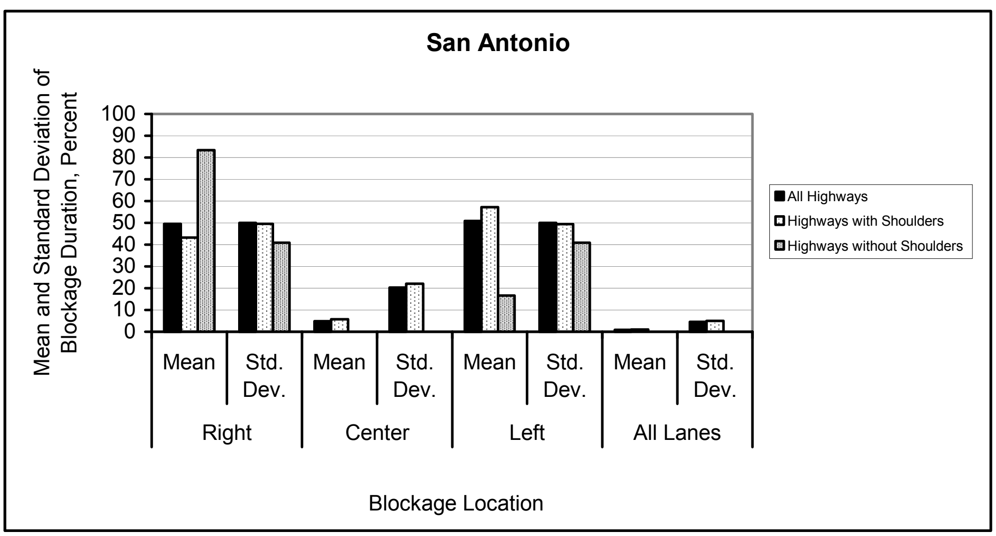

Figure 3.7b Percentage of Total Blockage Duration by Cross Section Location for Freeways with and without Shoulders (San Antonio)

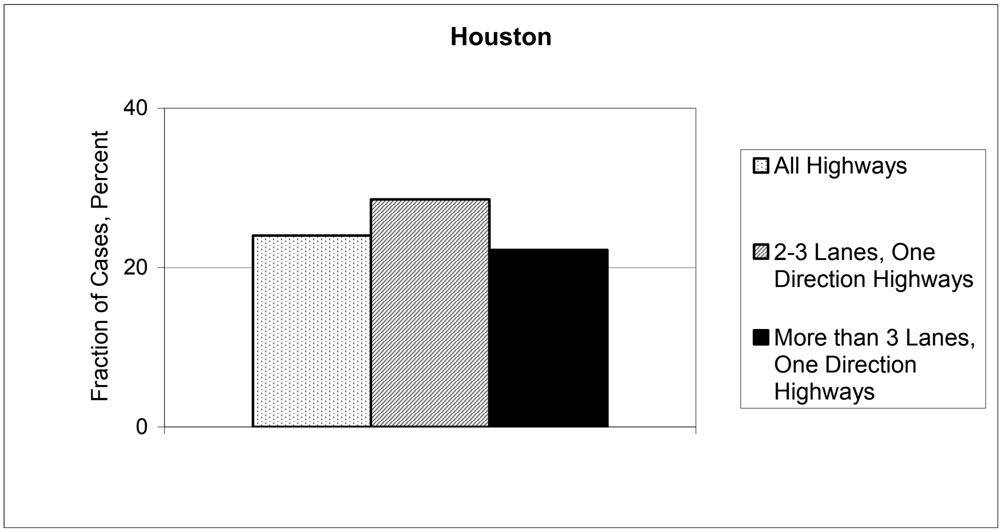

Figure 3.8a Fraction of Cases where All Lanes Were Blocked (Houston)

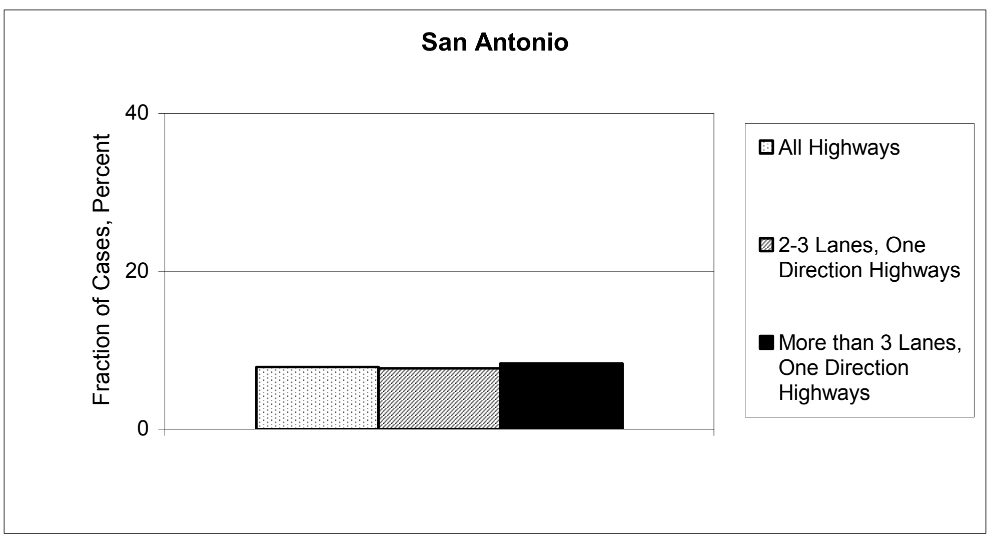

Figure 3.8b Fraction of Cases where All Lanes Were Blocked (San Antonio)

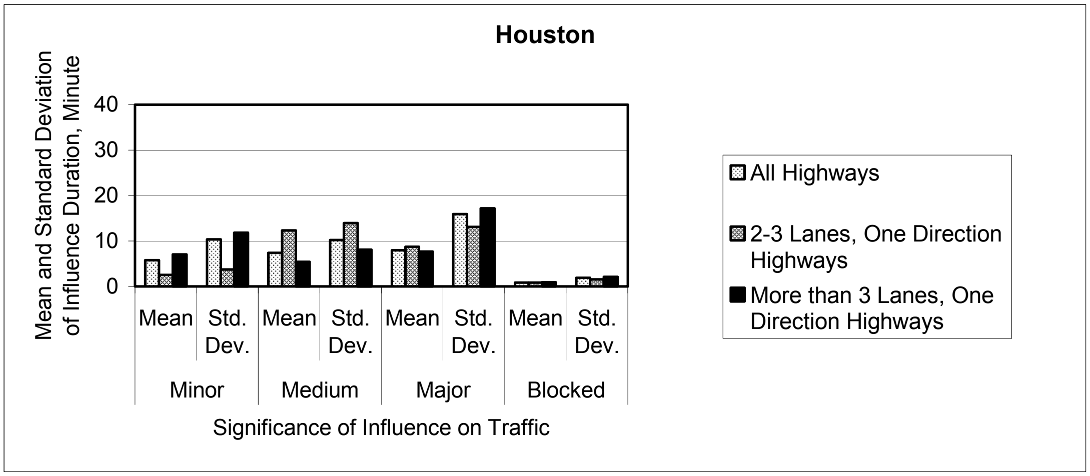

Figure 3.9a Duration of Incident Influence on Traffic, Actual Time (Houston)

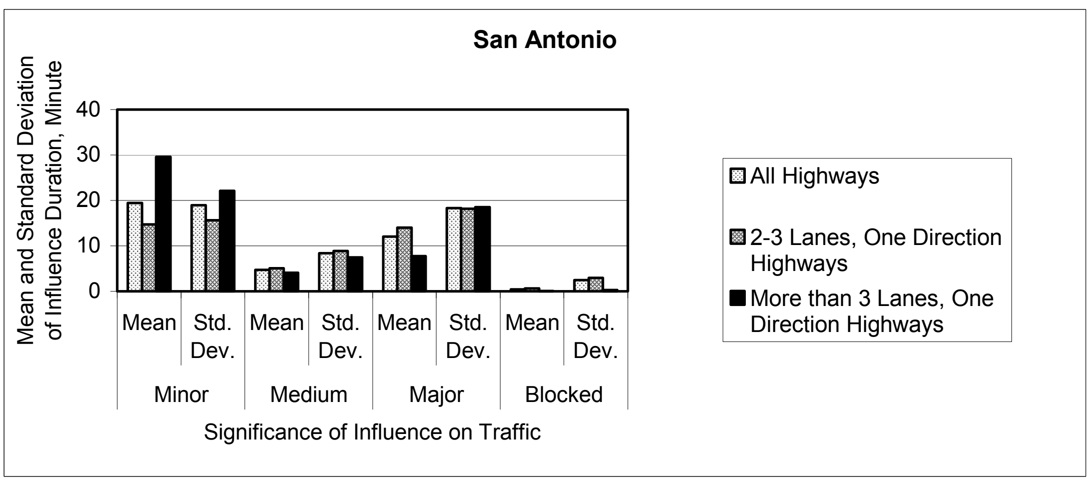

Figure 3.9b Duration of Incident Influence on Traffic, Actual Time (San Antonio)

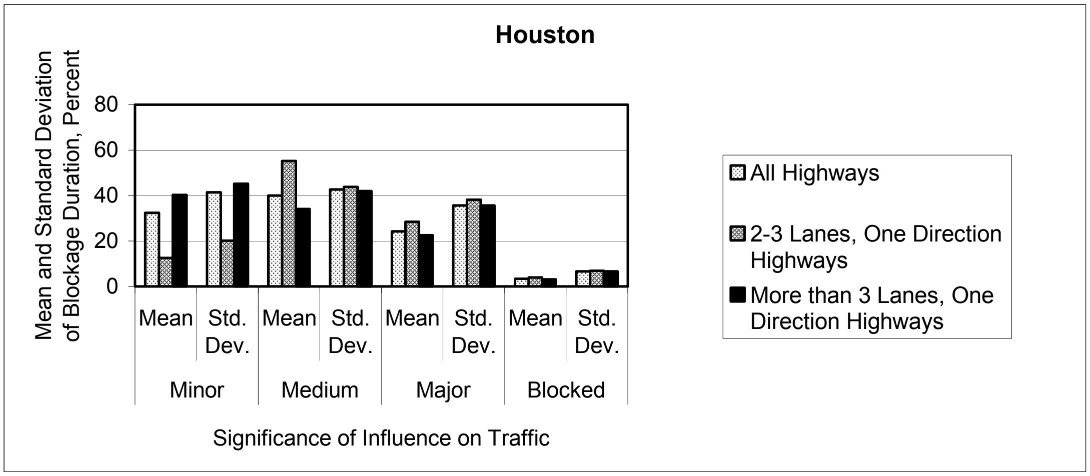

Figure 3.10a Percentage of Total Observed Traffic Influence Time by Cross Section Location (Houston)

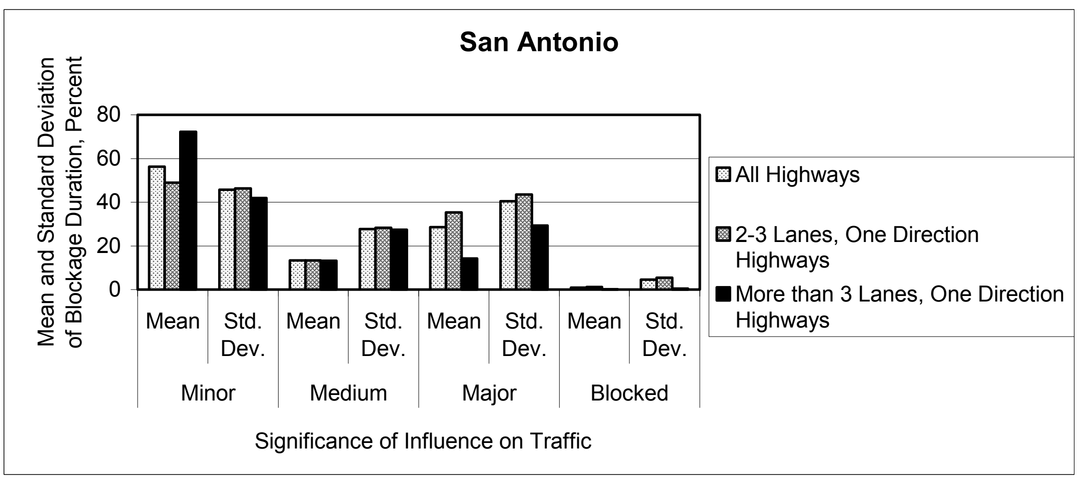

Figure 3.10b Percentage of Total Observed Traffic Influence Time by Cross Section Location (San Antonio)

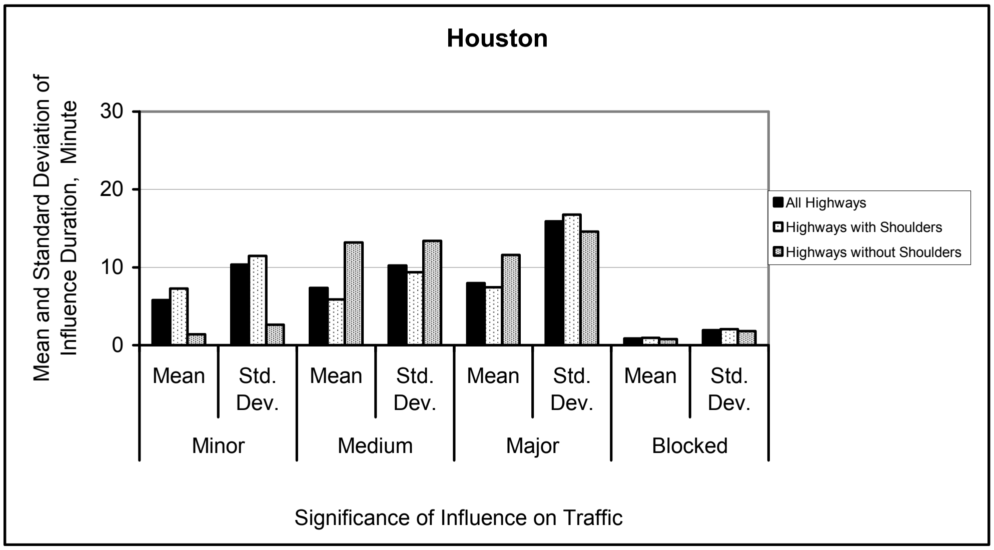

Figure 3.11a Duration of Incident Influence on Traffic for Freeways with and without Shoulders, Actual Time (Houston)

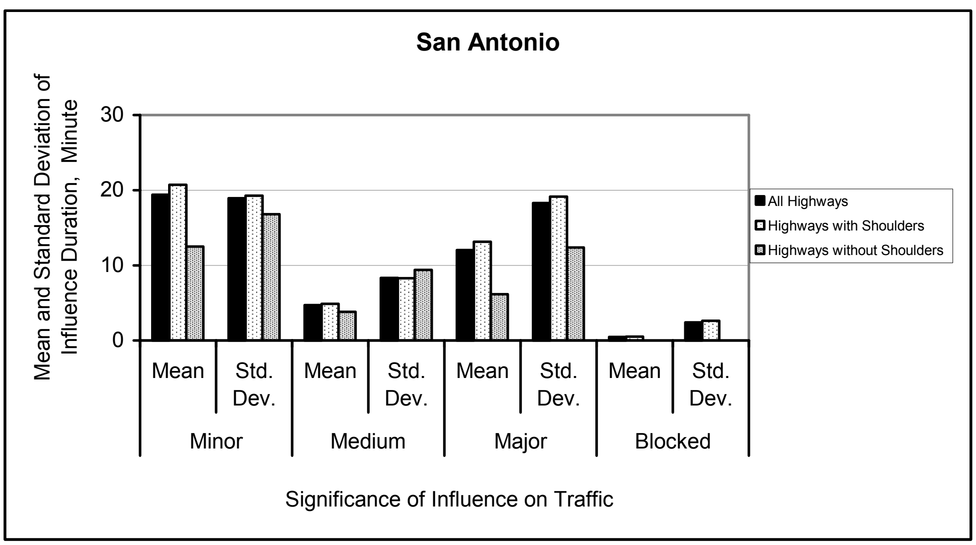

Figure 3.11b Duration of Incident Influence on Traffic for Freeways with and without Shoulders, Actual Time (San Antonio)

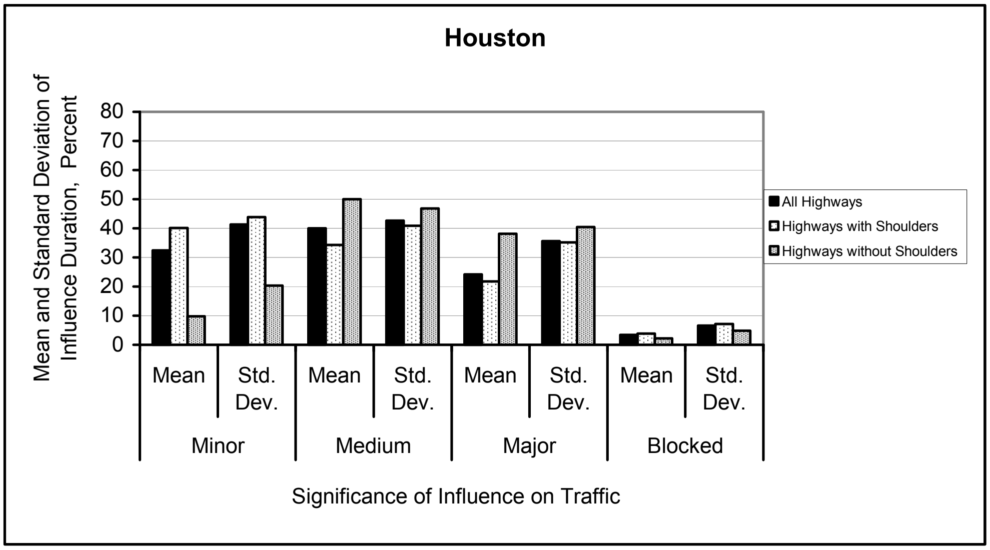

Figure 3.12a Percentage of Total Observed Traffic Influence Time by Cross Section Location for Freeways with and without Shoulders (Houston)

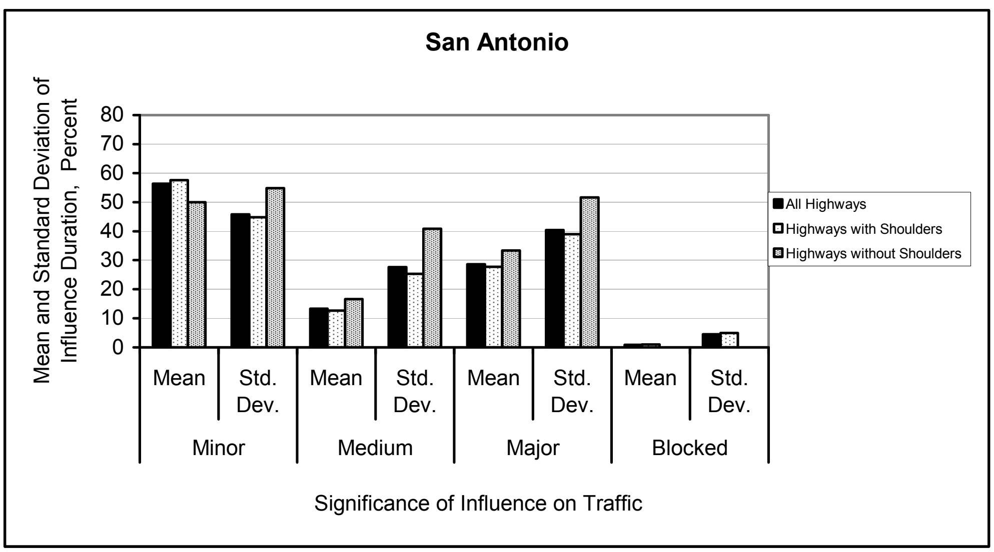

Figure 3.12b Percentage of Total Observed Traffic Influence Time by Cross Section Location for Freeways with and without Shoulders (San Antonio)

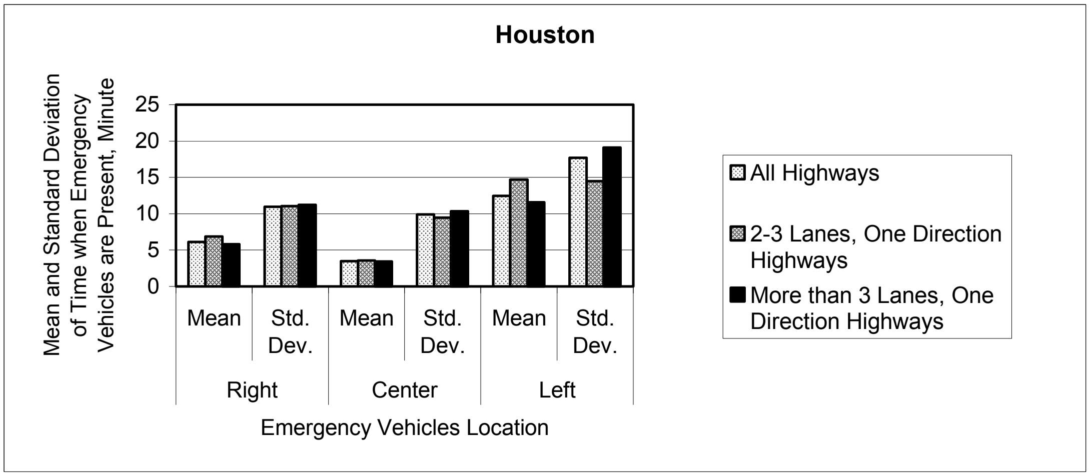

Figure 3.13a Duration of Emergency Vehicle Presence by Cross Section Location, Actual Time (Houston)

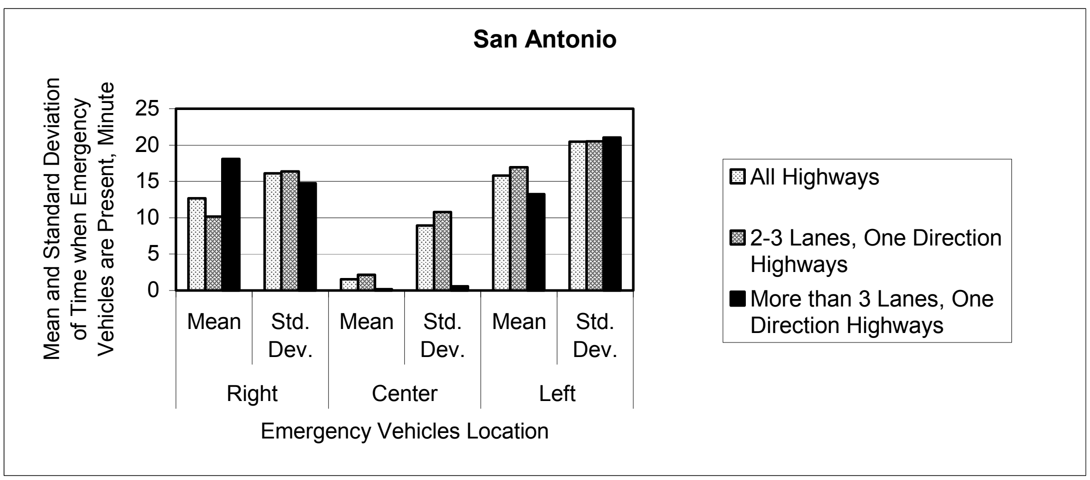

Figure 3.13b Duration of Emergency Vehicle Presence by Cross Section Location, Actual Time (San Antonio)

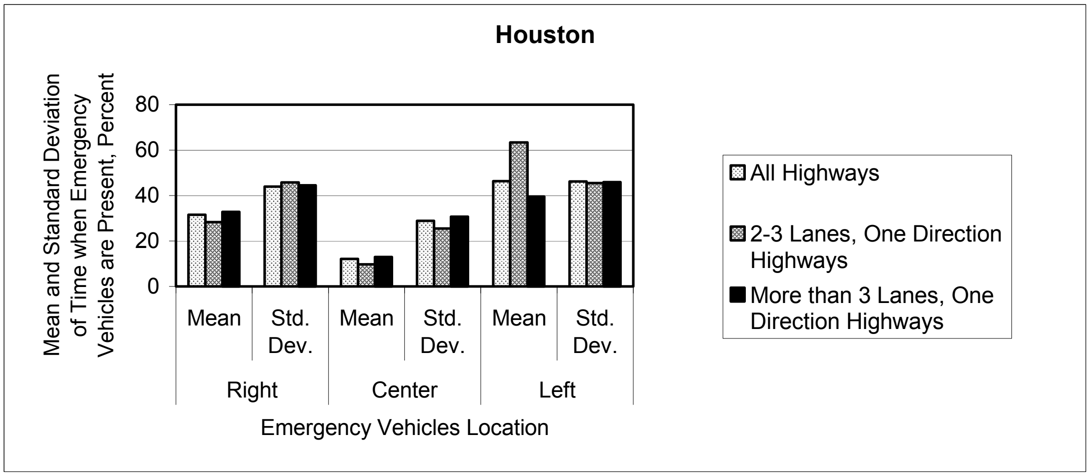

Figure 3.14a Duration of Emergency Vehicle Presence as Percentage of Total Blockage Duration (Houston)

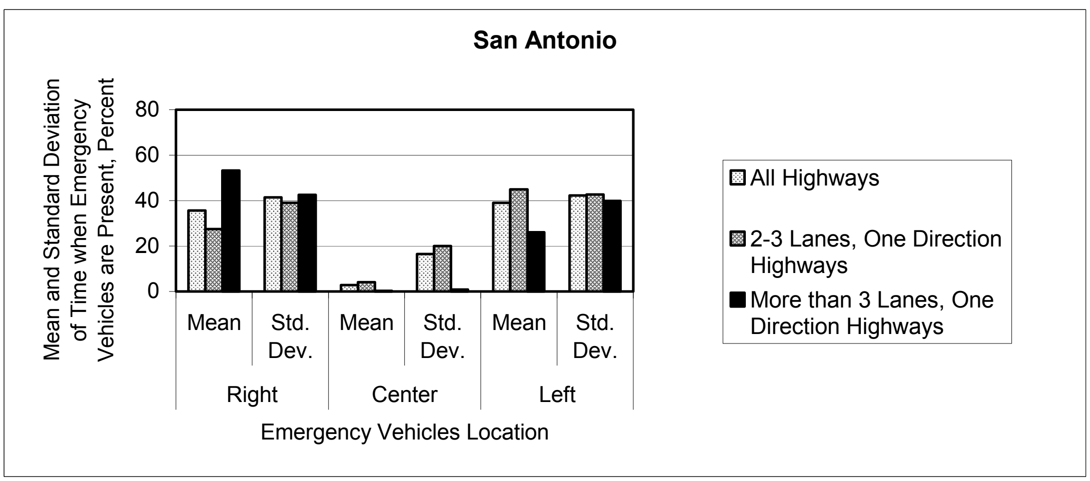

Figure 3.14b Duration of Emergency Vehicle Presence as Percentage of Total Blockage Duration (San Antonio)

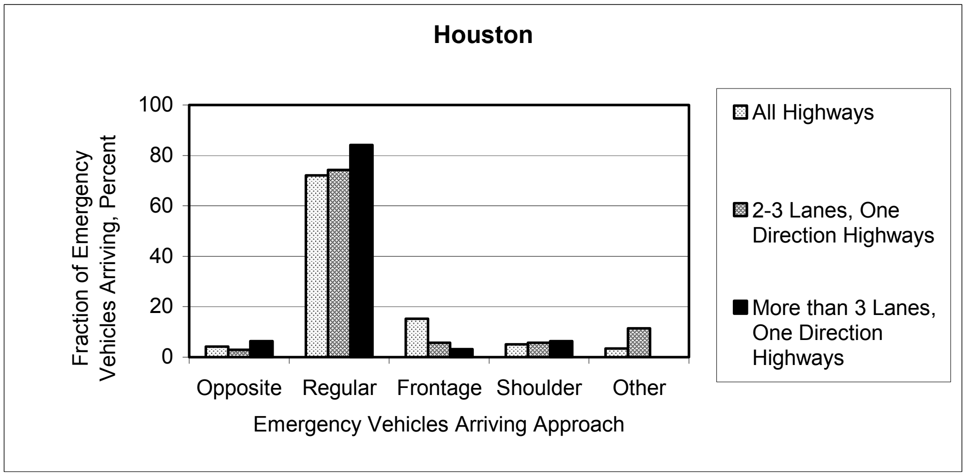

Figure 3.15a Emergency Vehicle Approach Paths (Houston)

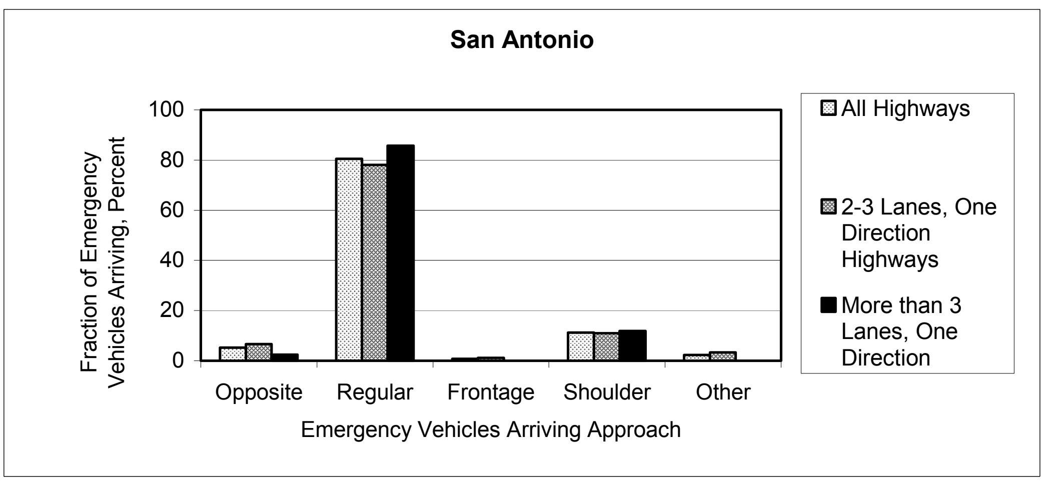

Figure 3.15b Emergency Vehicle Approach Paths (San Antonio)

INCIDENT ANALYSES

All observed accidents were examined by answering a variety of questions relating to experience-based expectations. The following sections present the questions and the observed answers.

Incident Cross-Sectional Frequency (Figures 3.2a and 3.2b)

The first question was whether any part of the cross section was over-represented. One might expect the right side to be the most frequent accident location given that most entrance-exit activity takes place on the right. However, results did not totally support this hypothesis.

1. As shown in Figures 3.2a and 3.2b, on two- and three-lane highways, accidents occurred more often in the left lane than in the right lane, for both cities. Houston highways with more than three lanes in one direction had a similar accident distribution, but in San Antonio, right-side accidents were twice as frequent as left-side accidents. Overall, observed incidents in Houston were more often on the left (52 percent left versus 31 percent right). However, San Antonio observations yielded a slightly greater fraction of right-side incidents (48 percent right versus 46 percent left).

2. Accident frequency in the center lanes was minimal for both cities on all highways. The percentage of accidents in center lanes was higher on highways with more than three lanes in one direction. This frequency was 16.7 percent in San Antonio and 25 percent in Houston.

3. The left-side accident frequency was significantly reduced as the number of freeway lanes increased in both cities. Comparing two- to three-lane freeways and those with more than three lanes, on smaller highways, left-side occurrences comprised 66.67 percent (Houston) and 53.6 percent (San Antonio) of all accidents, but for larger highways, those left-side values were 43.75 percent and 25.0 percent, respectively.

Cross-Sectional Blockage Location Frequency (Figures 3.3a and 3.3b)

Virtually all observed accidents resulted in one or more lanes being blocked for some duration. Fractions of observed accidents that blocked right, center, or left lanes are shown in Figures 3.3a and 3.3b. Because incidents often blocked both right and center, center and left, or all lanes, the percentage in the figures typically sum to more than 100 percent.

1. On two- to three-lane highways, left-side blockage was more frequently observed than right side blockage for both cities. For three or more lane freeways, left-side blockage was more frequent than right-side in Houston, but not in San Antonio.

2. Center-lane blockage was rarely observed in San Antonio, around 10 percent of all incidents, but was much higher in Houston, representing almost 50 percent of all incidents.

3. Blockage of all lanes was more frequent in Houston, where around 25 percent of all accidents caused this situation. In San Antonio this value did not exceed 10 percent.

Duration of Blockage (Figures 3.4, 3.5, 3.6, and 3.7)

The analysis includes the duration of lane blockages, as well as the percentage of total observed blockage time for left, center, and right-side lanes. Data was analyzed separately for freeways with and without shoulders.

1. Figures 3.4a and 3.4b indicate that mean duration of center lane blockage was minimal, generally less than 5 minutes. Figures 3.5a and 3.5b show that center blockage varied from 3 percent to 8 percent of the total blockage time in San Antonio, and from 12 percent to 28 percent in Houston. The Houston data emphasize the fact that although center-lane blockages were short in duration for three or more lane freeways, they represented a large fraction of total blockage time.

2. One might expect that left-side lane blockages would have longer durations than right-side and Houston data clearly showed this both in terms of duration and in percentage of total blockage time. However, for San Antonio, longer duration left-side blockage was true only for two- to three-lane freeways but was not true for freeways with more than three lanes.

3. Generally, blockage duration was longer in San Antonio than in Houston, with right-lane blockages averaging 17 minutes versus 7 minutes in Houston. Left-lane blockages in Houston averaged less than 15 minutes, compared to 21 minutes in San Antonio. In all cases, standard deviations were equal to or greater than mean values, indicating significant variation in time.

4. The durations of incidents blocking all lanes were very short, averaging 1 to 2 minutes for both cities.

5. Houston data indicated that on freeways without shoulders average blockage duration on the left-side contained 78 percent of total blockage duration compared to 50 percent on freeways with shoulders. Right-side and center-blockage duration, correspondingly, are shorter for freeways without shoulders. San Antonio data showed strong redistribution of blockage duration from the left to the right-side. On freeways without shoulders right-side blockage duration was 83 percent of total blockage duration, while only 43 percent on freeways with shoulders.

Fraction of Cases Where All Lanes Were Blocked (Figures 3.8a and 3.8b)

As just noted, durations of total freeway blockages were minimal, though in Houston, such events were frequent.

For all freeways, all lane blockages were more frequent in Houston. This situation was observed in around 25 percent of the investigated Houston accidents and around 7 percent of the San Antonio incidents.

Houston data showed that two- to three-lane highways have a higher fraction of such cases (28 percent) than larger, three-or-more-lane freeways (18 percent).

Duration of Influence on Traffic (Figures 3.9, 3.10, 3,11, and 3.12)

Even though damaged vehicles and emergency vehicles are removed from freeway main lanes, their presence on shoulders can still influence traffic. Judgments regarding influence upon traffic were based upon observed speed compared to normal speeds for that freeway at that time of day. Qualitative descriptions of observed effects using labels of "minor", "medium", or "major" were used. Generally "minor" described cases of less than10 mph speed reduction, while "medium" and "major" described cases of 10 to 20 mph and greater than 20 mph reduction correspondingly. This classification based on the "85-percentile speed difference" methodology for traffic safety estimation (Ref 17).

This analysis was conducted for actual influence time upon left, center, and right lanes (Figures 3.9a and 3.9b), as well as the percentage of total influence time experienced by left, center, and right lanes (Figures3.10a and 3.10b), as well as for freeways with and without shoulders (Figures 3.11 and 3.12).

On Houston freeways, the influence on traffic is short in duration, generally 5 to 10 minutes for all influence-classes. San Antonio data show that influence duration is generally longer, particularly with regard to minor influences on more than three-lane freeways, where the duration approaches a 30-minute average.

Houston data indicate approximately equal distribution of influence duration among the three severity classes for larger highways, and predominant medium influence for two- and three-lane highways. However, San Antonio data indicate longer duration and frequencies of minor severity influence for both types of highways.

Generally, both data sets show that accident influence on traffic operation on freeways with more than three lanes is less significant than on two- to three-lane highways. San Antonio data show minor influences on larger highways represent 72 percent of total blockage time versus 49 percent for two- to three-lane freeways and Houston data show minor influences representing 40 percent of blockage time on large freeways versus 12 percent for small freeways. At the same time, the duration of major influence reduces as well, from 28 to 22 percent for Houston, and from 35 to 14 percent for San Antonio.

The comparison of the influence on traffic for freeway with and without shoulders showed that accident's influence on traffic is stronger on freeways without than with shoulders for both cities. While on Houston freeways with shoulders medium and major influence comprised 55 percent total influence duration, on freeways without shoulders such influence was 88 percent. The difference was smaller on San Antonio freeways where they comprised 39 and 49 percent, correspondingly.

Duration of Emergency Vehicle Presence (Figures 3.13 and 3.14)

The duration of the presence of emergency vehicles at an incident location can be a surrogate for accident or incident severity. It can also be indicative of difficulty associated with incident clearance due to limiting geometric features. Using video records of incidents, researchers measured the duration of all types of emergency vehicles, including enforcement vehicles was measured.

For both cities, on two- to three-lane highways, emergency vehicles spent a longer time on the left side compared to the right and minimal time in the center. The combined data sets produced a mean value of the duration of emergency vehicles present on the left side of 15-17 minutes, or 45-62 percent of total blockage time. For the center location, these times are 2-3 minutes, or 5-10 percent.

Houston's large, four-or-more-lane freeways also had larger left-side emergency vehicle durations; however, San Antonio's large freeways showed slightly larger right-side durations. On San Antonio's freeways with more than three lanes, emergency vehicles were observed on the right side about 53 percent of the total blockage time, compared to 32 percent in Houston.

Emergency Vehicle Approach Paths (Figures 3.15a and 3.15b)

Freeway geometry can severely limit the ability of emergency vehicles to reach an incident site. A freeway full of stopped cars and having no shoulders can mean no safe path for emergency vehicle access is available. Again, video records were used to determine the access path used by whatever emergency vehicle responded to the incident.

The predominant emergency vehicle arrival path was using regular direction main lanes and shoulders. On highways with more than three lanes, this approach was observed in 91 percent of the Houston cases and in 98 percent of the San Antonio cases. For two- to three-lane highways this approach was used in 80 percent and 89 percent of the cases for Houston and San Antonio, respectively. Correspondingly, on two- to three-lane highways in Houston, the other emergency vehicle arrival path was observed about 20 percent of the time, and 11 percent in San Antonio. On highways with more than three lanes, such an approach was observed in 9 percent and 2 percent for Houston and San Antonio, respectively. In this analysis the other approach includes opposite direction main lanes, frontage roads, and some time the median. Therefore, emergency vehicles usually gain access using main lanes traveling in the normal direction on large, four-or-more-lane freeways, but more frequently must use another path on two- and three-lane freeways.

CONCLUSIONS

For comparison of the Houston and San Antonio data, analysis of traffic conditions during the observed accidents was made. Eighty-three percent of the Houston accidents happened during high and medium traffic volume; however, in San Antonio 74 percent occurred during free flow conditions. Therefore, taking into consideration similar city characteristics, traffic control systems, incident management programs, freeway designs, and weather conditions, it is possible to assume that the major difference between the analyzed data is traffic volume.

Analysis leads to the following conclusions:

1. On two- to three- lane freeways more accidents happened in the left lane than in the right lane. On such highways it may be that left-lane traffic is significantly affected by the right-lane traffic, which is influenced by exit and entrance operations and characterized by slower speed and higher speed variation. Traffic weaving, between right and middle lanes, is observed. At high traffic volume and with frequent exit/entrance ramps, significant speed reduction exists on right and middle lanes, due to merging vehicles. At the same time, the speed in the left lane continues to be higher than that in the right and middle. This makes the process of merging from the middle to the left more complex, with higher probability of driver error that, in turn, increases accident frequency in the left lane. At the same time, drivers in the right lane, psychologically, are better prepared for frequent situation changes, have greater attention, and react more adequately. On highways with more than three lanes, at low traffic volume, accidents occurred more frequently on the right side, while at high traffic volumes, left-side accidents became more frequent, what can be explained by the above mentioned reason also.

2. On two- to three- lane freeways left side blockages are of longest duration. On freeways with more than three lanes, at low traffic volume, right side blockages are of longest duration, but at high volumes, left-side accidents required longer clearance times. This phenomenon can possibly be explained by the fact that it is much more difficult for the emergency team to work on the freeway's left side with smaller space and faster traffic than on the right side. Also, it must be noted that at low traffic volumes the police preferred to shift the involved vehicles to the right, even if accident occurred on the left.

3. For all highways at low traffic volume, accidents usually have minor effects on through traffic. As traffic volume increases, the influence on traffic increases as well. The interactive effect of traffic volume and speed influence due to accidents is less significant on highways with more than three lanes. For all observed freeways, the absence of shoulders increase duration of medium and major accident's influence on through traffic. At traffic volume growth, this influence became more significant.

4. On small two- to three- lane freeways, emergency vehicles frequently must find an arrival path other than the main freeway lanes, but for large, three-or-more-lane freeways, the travel direction of the main lane is the usual access path.

SUMMARY

Using video surveillance capabilities at the San Antonio and Houston traffic control centers, a large number of freeway incidents were examined. From the detailed analysis a clear need for a pathway for emergency vehicles to reach incident sites, as well as a need for a haven for disabled or damaged vehicles were identified. Such a haven would reduce incident's influence on traffic, permit faster incident clearing and re-opening of main lanes. An obvious solution to both the access path and haven problems is a paved shoulder. This led to a recommendation to maintain a minimum eight feet wide shoulder on, at least, the freeway right side for freeways with three or fewer lanes and maintenance of minimum eight feet wide shoulders on both the left and right sides on freeways with more than three lanes per direction. The recommendation of a shoulder, at least on the right side of two- to three-lane freeways, is based on the assumption that roadway width easily allows to-merge vehicles involved to approach the accident and emergency teams to approach on the right side. On four-or-more-lane freeways this will significantly increase the hazard for drivers and emergency teams, as well as increase the probability of a secondary accident. Recently obtained data clearly shows that shoulders can reduce duration of accident influence on through traffic by major and medium significance, from 10 to 30 percent, depending on traffic volume, which carries significant potential for traffic operation and safety improvements.

CHAPTER 4 CASE STUDIES OF OPERATIONAL FLEXIBILITY DESIGN CONCEPTS

The operational flexibility concepts described in the previous sections can best be described through application to a case study freeway. The study team has had significant experience dealing with the Loop 1 freeway in Austin, Texas. Using this knowledge base, the researchers selected this freeway for case study application. This chapter describes Loop 1 bottleneck sites, suggested solutions, and design concepts that could enable easier solution implementation.

HISTORY OF THE CASE STUDY FACILITY

Loop 1, in Austin, Texas, is plagued by bottlenecks and serious recurrent congestion, which frustrates and delays commuters during the a.m. and p.m. peak periods. This situation prompted the Texas Department of Transportation (TxDOT) to ask the Center for Transportation Research of The University of Texas at Austin to conduct a study of the operational problems on an 11-mile section of Loop 1 from the US 183/Loop 1 interchange in the north, to the end of Loop 1 at Southwest Parkway in the south. A project team studied and collected data on Loop 1 operational and geometric characteristics and considered how operational flexibility might apply to the Loop 1 bottleneck locations.

All entrance and exit ramp volumes were counted using infrared sensing devices. Aerial photographs supplied by TxDOT were used to collect data on geometric conditions, such as number of lanes, lengths of freeway sections, and the lengths of acceleration and deceleration lanes. Also, periodic on-site observations were performed to locate and observe areas of recurrent congestion.

Once data had been collected, two approaches were examined to improve Loop 1 freeway performance. One approach involved using freeway simulation software, FREQ and CORSIM, to analyze how ramp metering, lane additions, and High Occupancy Vehicle (HOV) lanes can improve troubled freeway section performance. Another approach examined the feasibility of correcting any discrepancies between existing geometric characteristics of Loop 1 and the design standards set forth by the American Association of State Highway and Transportation Officials (AASHTO). Having identified solutions, the researchers looked at geometric elements that could enable solution implementation, identifying them as operational flexibility design elements.

DESCRIPTION OF LOOP 1

Loop 1 is an urban north-south controlled-access freeway. Built in pieces during the 1970s and 80s, it links Austin's central business district (CBD) with outlying residential areas. In recent years, rapid industrial and population growth to the north and south of the Austin CBD has caused traffic volumes on Loop 1 to increase steadily. As a result, significant congestion exists on many freeway sections during morning and evening peak hours. Compounding the congestion problems is the lack of efficient alternative routes. For example, Lamar Boulevard and Burnet Road are arterials that parallel Loop 1, but inadequate capacity and greater travel times on those routes compel commuters to use Loop 1.

The study area for this project is an 11-mile section of Loop 1 from the US 183 interchange in the north to the US290/Southwest Parkway interchange in the south. To identify, study, and solve the congestion problems, researchers collected data on ramp and main lane volumes, freeway travel times, and freeway geometry. Also, field observations were made periodically to supplement the data and to confirm bottleneck presence.

DETERMINING RAMP VOLUMES

Traffic volumes for all Loop 1 entry and exit ramps between US 183 and US 290 were counted using infrared sensors. For each ramp, 15-minute volumes were collected over a continuous 48-hour period. Because traffic volumes during the summer were assumed to differ from those in the fall, all ramp counts used to identify and study traffic flow operations were collected in October, November, and December of 1995. Summer ramp counts were done in July and August of 1995, but were used only to compare summer and fall traffic volumes.

Equipment used for the ramp counts consisted of an infrared sensor, an aluminum plate reflector, and a traffic data acquisition (TDA) unit with a 12-volt battery power supply. Setting up this equipment first involved attaching the infrared sensor and the reflector to poles on opposite sides of the ramp. Second, the sensor and the reflector were aligned so that when there was no obstruction, the infrared rays emitted by the sensor were reflected back to the sensor. Data collected by the TDA units were downloaded on-site with a laptop computer.

Once the equipment was set up and functioning, a vehicle was counted when the infrared light-rays emitted by the sensor were interrupted by a passing vehicle, which caused a switch closure that, in turn, advanced the counter of the TDA unit. This process counts traffic volumes for any user-specified time interval. For example, in this project the TDA units were set up to count volumes at 15-minute intervals.

For a single-lane ramp, the data obtained were the actual number of vehicles using the ramp. However, for a two-lane ramp, the numbers were lower than the actual number of vehicles using that ramp because two vehicles can simultaneously pass through the sensor. Therefore, the regression equation given below was used to estimate the actual number of vehicles using the two-lane ramp.

$$\text{Total Ramp Volume} = 1.0088865*X + 0.0003595*X^2$$

X = 15-minute vehicle volume count given by the TDA system

MAIN LANE COUNTS

Until recently, manual counts were necessary to obtain main lane volumes. The infrared system described above was not capable of counting the freeway main lanes. Therefore, southbound peak hour counts were done on a section just north of the US 183 entrance ramp from 6:30 a.m. to 9:00 a.m. and from 4:30 p.m. to 6:30 p.m. The northbound counts were done just south of the Southwest Parkway entrance ramp for the same times.

In the summer of 1996 an infrared system similar to that described above was introduced to count the main lanes. This new system, installed underneath overpasses at the north and south end of Loop 1, counts the main lanes, in both directions, continuously over 24 hours. At the time of this report, only the south end system was functional; main lane counts from this location are displayed in Tables 4.1 and 4.2.

Table 4.1 Southbound Main Lane Counts
Just North of the Southwest Parkway Interchange

Date	7:00-8:00	8:00-9:00	16:00-17:00	17:00-18:00	18:00-19:00	ADT
7/29/96	1061	1364	3565	4535	3419	
9/16/96	1091	1352	3405	4051	3358	30221
9/17/96	1118	1279	3469	4101	3170	31640
9/18/96	1180	1404	3518	3904	3681	32013
9/19/96	1129	1326	3335	3998	3226	32068
9/20/96	1113	1304	3421	4016	3086	32119
Ave. vol. (vph)	1115	1338	3452	4101	3323	31612
Ave. 15 min. vol.	279	335	863	1025	831	

Table 4.2 Northbound Main Lane Counts
Just North of the Southwest Parkway Interchange

Date	7:00-8:00	8:00-9:00	16:00-17:00	17:00-18:00	18:00-19:00	ADT
7/29/96	5194	4152	2033	2120	2025	
9/16/96	5552	4160	1920	1921	1877	37306
9/17/96	5605	4442	2018	1987	1912	37174
9/18/96	5530	4310	2006	1976	1964	37053
9/19/96	5722	4158	2058	1998	2070	37757
9/20/96	5271	4149	2237	2178	2234	39474
Ave. vol. (vph)	5479	4229	2045	2030	2014	37753
Ave. 15 min. vol.	1370	1057	511	508	503	

Combining the ramp counts with the main lane counts, researchers derived a freeway demand for each freeway section.

GEOMETRY

The geometric characteristics of Loop 1 were obtained from aerial photographs and on-site investigations. Data were collected on lengths of freeway subsections, number of lanes on each subsection, lateral clearance, nature of ramps (on- or off-ramps), number of lanes on each ramp, and whether the subsection was a weaving area. Tables 4.3 and 4.4 describe the subsections and their corresponding geometric characteristics for the southbound and northbound directions, respectively.

CAPACITY ANALYSIS

Also given in Tables 4.3 and 4.4 are the theoretical capacities for each section. As defined by the Highway Capacity Manual (HCM), section capacities are a function of the number of lanes, lane width, lateral clearance, design speed, grade, the percentage of heavy vehicles, and whether the section is defined as a weaving area. Under ideal conditions, defined by 12 foot lanes, at least 6 feet of lateral clearance from obstructions on both sides of the freeway, level terrain, 0 percent heavy vehicles, and a 70 mph design speed, the capacity for non-weaving sections is 2,000 to 2,300 passenger cars per hour per lane. For freeway sections where weaving maneuvers affect freeway flow, capacity is reduced to 1,900 passenger cars per hour per lane.

Loop 1 is a modern freeway whose generally lateral clearance and design speed are equal to the HCM ideal. Also, it is assumed that the effect owing to grade and the percentage of heavy vehicles is negligible.

Table 4.3 Northbound Geometric Conditions and Capacity Analysis

Subsection Description	Length ft	# of Lanes	Lane Width ft	Lateral Clearance Left ft	Lateral Clearance Right ft	Weaving	Capacity pcph
Before Southwest Parkway Ent.	-	2	12	-	-	N	4000
Southwest Parkway Ent. to Loop 360 Ex.	3443	3	12	4	12	N	6000
Loop 360 Ex. to Loop 360 Ent.	1500	3	12	2	2	N	6000
Loop 360 Ent. to Barton Skyway Ex.	4409	3	12	8	12	N	6000
Barton Skyway Ex. to FM 2244 Ex.	1964	3	12	8	12	N	6000
FM 2244 Ex. to Barton Skyway Ent.	1475	3	11	2	2	N	5760
Barton Skyway Ent. to FM 2244 Ent.	1720	3	11	2	2	N	5760
FM 2244 Ent. to 1st -5th St. Ex.	3414	4	11	4	6	N	7680
1st -5th St. Ex. to Enfield Ex.	1765	3	12	5	8	N	6000
Enfield Ex. to 6th St. Ent.	1225	2	11	5	10	N	3840
6th St. Ent. to Enfield Ent.	1810	3	12	6	12	N	6000
Enfield Ent. to Windsor Ex.	2154	4	11	6	6	Y	7296
Windsor Ex. to Windsor Ent.	305	3	12	6	16	N	6000
Windsor Ent. to Westover Ex.	1750	4	11	6	6	Y	7296
Westover Ex. to Westover Ent.	1460	3	12	7	10	N	6000
Westover Ent. to 35th St. Ex.	1640	4	12	8	6	Y	7600
35th St. Ex. to 35th St. Ent.	670	3	12	6	10	N	6000
35th St. Ent. to 45th St. Ex.	3779	3	12	6	8	N	6000
45th St. Ex. to 45th St. Ent.	2039	3	12	8	10	N	6000
45th St. Ent. to FM 2222 Ex.	2694	4	12	6	8	N	8000
FM 2222 Ex. to FM 2222 Ent.	720	3	12	10	12	N	6000
FM 2222 Ent. to Far West Ex.	5484	3	12	6	12	N	6000
Far West Ex. to Far West Ent.	1760	3	12	6	10	N	6000
Far West Ent. to Anderson Ex.	1640	4	12	6	10	Y	7600
Anderson Ex. to Steck Ex.	1860	3	12	6	10	N	6000
Steck Ex. to US 183 Ex.	2779	3	12	5	8	N	6000
US 183 Ex. to US 183 Ex. (2 lane)	1540	4	11	8	8	N	7680

Table 4.4 Southbound Geometric Conditions and Capacity Analysis

SS#	Subsection Description	Length m	# of Lanes	Lane Width ft	Lateral Clearance Left ft	Lateral Clearance Right ft	Weaving	Capacity pcph
1	Before US 183 Ent.	-	2	12	0	0	N	4000
2	US 183 Ent. to Steck Ex.	551.69	4	11	8	8	Y	7296
3	Steck Ex. to Steck Ent.	670.56	3	12	6	10	N	6000
4	Steck Ent. to Far West Ex.	694.94	4	12	6	10	Y	7600
5	Far West Ex. to West Anderson Ent.	910.13	3	12	6	10	N	6000
6	West Anderson Ent. to Far West Ent.	579.12	3	12	6	10	N	6000
7	Far West Ent. to FM 2222 Ex.	958.29	3	12	6	10	N	6000
8	FM 2222 Ex. to FM 2222 Ent.	573.02	3	11	6	10	N	5760
9	FM 2222 Ent. to 45th St. Ex.	545.59	4	12	8	6	N	8000
10	45th St. Ex. to 45th St. En.	524.26	3	12	8	10	N	6000
11	45th St. En. to 35th St. Ex.	752.86	4	12	8	6	N	8000
12	35th St. Ex. to 35th St. Ent.	623.62	3	12	6	10	N	6000
13	35th St. Ent. to Westover Ex.	499.87	4	12	7	5	Y	7600
14	Westover Ex. to Westover Ent.	423.67	3	12	8	10	N	6000
15	Westover Ent. to Windsor Ex.	565.71	4	11	6	6	Y	7296
16	Windsor Ex. to Enfield Ex.	346.25	3	11	6	6	N	5760
17	Enfield Ex. to Lake Austin Ex.	536.45	3	12	6	10	N	6000
18	Lake Austin Ex. to 1st-5th St. Ex.	292.61	3	12	6	10	N	6000
19	1st-5th St. Ex. to Enfield Ent.	536.45	2	11	4	10	N	3880
20	Enfield Ent. to 1st-5th St. & Lake Austin En.	310.9	3	12	6	8	N	6000
21	1st-5th St. & Lake Austin Ent. to Bee Caves Ex.	1014.4	4	12	2	4	N	8000
22	Bee Caves Ex. to Barton Skyway Ex.	579.12	4	11	2	2	N	7680
23	Barton Skyway Ex. to Bee Caves Ent.	434.04	3	11	2	2	N	5760
24	Bee Caves Ent. to Barton Skyway Ent.	496.82	3	12	6	10	N	6000
25	Barton Skyway Ent. to Loop 360 Ex.	810.77	3	12	6	10	N	6000
26	Loop 360 Ex. to EB Loop 360 Ex.	1066.8	2	12	4	12	N	4000
27	EB Loop 360 Ex. to Loop 360 Ent.	435.86	2	12	8	12	N	4000
28	Loop 360 Ent. to Southwest Parkway Ex.	450	3	12	4	12	N	6000

CRITERIA FOR DEFINING BOTTLENECKS

Speed is the fundamental measure of effectiveness for identifying freeway bottlenecks. Reoccurring low speeds on a freeway section usually indicate the presence of a bottleneck or of some other incident. One speed measure is vehicle-running speed, which is found by dividing the distance traveled by the time the vehicle is in motion. Another speed measure is average spot speed, which is the arithmetic mean of the speeds of all traffic at a specified point. Either method can be used to identify areas of reoccurring low freeway speeds. The following paragraphs discuss criteria that can be used to identify locations that will produce significant speed reductions.

CRITERIA

Four basic identifiers were used to determine the possible presence of bottlenecks: lane drops following exit ramps, demand exceeding capacity following entrance ramps, weaving sections, and acceleration-lane lengths. On-site observation was used to confirm these concepts in addition to identifying other bottlenecks. Using the four identifiers, Tables 4.5 and 4.6 shows potential and observed bottlenecks on freeway sections for southbound and northbound directions, respectively. The "Observed" column of the tables indicates locations determined by the project team to be a bottleneck location. The table column also indicates whether this condition existed during the morning, evening, or both peak periods.

Table 4.5 Likely Bottlenecks for Southbound Loop 1

	Criteria for bottleneck identification						
	Lane	Demand				Observed	
Section Description	Drop	AM	PM	Weaving	Accel	AM	PM
US En. 183 to Steck En.	-	-	-	X	-	X	-
Steck En. to Steck Ex.	-	-	-	X	-	X	-
Steck En. to Far West Ex.	-	-	-	-	-	X	-
Far West Ex. to West Anderson En.	X	-	-	-	-	X	-
West Anderson En. to Far West En.	-	-	-	-	X	X	-
Far West En. to FM 2222 Ex.	-	X*	-	-	X	X	-
FM 2222 Ex. to FM 2222 En.	-	-	-	-	-	X	-
FM 2222 En. to 45th St. Ex.	-	-	-	-	X	X	-
45th St. Ex. to 45th St. En.	X	X	-	-	-	X	-
45th St. En. to 35th St. Ex.	-	-	-	-	-	X	-
35th St. Ex. to 35th St. En.	X	X*	-	-	-	-	X
35th St. En. to Westover Ex.	-	-	-	-	-	-	-
Westover Ex. to Westover En.	X	X	-	-	-	-	-
Westover En. to Windsor Ex.	-	-	-	-	-	-	-
Windsor Ex. to Enfield Ex.	X	X	-	-	-	-	-
Enfield Ex. to Lake Austin Ex.	-	-	-	-	-	-	-
Lake Austin Ex. to 1st, 5th St. Ex.	-	-	-	-	-	-	-
1st, 5th St. Ex. to Enfield En.	X	-	-	-	-	-	-
Enfield En. to 1st, 5th & Lake Austin En.	-	-	-	-	-	-	-
1st, 5th & Lake Austin En. to Bee Caves Ex.	-	-	-	-	-	-	X
Bee Caves Ex. to B'Skyway Ex.	-	-	-	-	-	-	-
B'Skyway Ex. to Bee Caves En.	X	-	-	-	-	-	X
Bee Caves En. to B'Skyway En.	-	-	-	-	-	-	X
B'Skyway En. to Loop 360 Ex.	-	-	-	-	-	-	X
Loop 360 Ex. to EB Loop 360 Ex.	X	-	-	-	-	-	-
EB Loop 360 Ex. to Loop 360 En.	-	-	-	-	-	-	X
Loop 360 En. to S'W'Parkway Ex.	-	-	-	-	-	-	X

Table Legend

X = Theoretical presence of a bottleneck due to an indicated criterion
X^* = Theoretical presence of a bottleneck due to demand approaching capacity
AM = Morning peak
PM = Evening peak

Table 4.6 Likely Bottlenecks for Northbound Loop 1

	Criteria for bottleneck identification						
	Lane	Demand				Observed	
Section Description	Drop	AM	PM	Weaving	Accel.	AM	PM
Before Southwest Parkway Ent.	-	-	-	-	-	-	-
Southwest Parkway Ent. to Loop 360 Ex.	-	-	-	-	-	X	-
Loop 360 Ex. to Loop 360 Ent.	-	-	-	-	-	-	-
Loop 360 Ent. to Barton Skyway Ex.	-	X	-	-	-	-	-
Barton Skyway Ex. to Bee Caves Ex.	-	X	-	-	-	-	-
Bee Caves Ex. to Barton Skyway Ent.	-	X*	-	-	-	-	-
Barton Skyway Ent. to Bee Caves Ent.	-	X	-	-	-	-	-
Bee Caves Ent. to 1st, 5th St. Ex.	-	X*	-	-	-	X	-
1st, 5th St. Ex. to Enfield Ex.	X	-	-	-	-	-	-
Enfield Ex. to 1st, 6th St. Ent.	X	-	-	-	-	-	-
1st, 6th St. Ent. to Enfield Ent.	-	-	-	-	-	-	X
Enfield Ent. to Windsor Ex.	-	-	-	-	-	-	X
Windsor Ex. to Windsor Ent.	X	X	-	-	-	-	X
Windsor Ent. to Westover Ex.	-	-	-	-	-	-	X
Westover Ex. to Westover Ent.	X	X	-	-	-	-	X
Westover Ent. to 35th St. Ex.	-	-	-	-	-	-	X
35th St. Ex. to 35th St. Ent.	X	-	-	-	-	-	X
35th St. Ent. to 45th St. Ex.	-	-	X	-	X	-	-
45th St. Ex. to 45th St. Ent.	-	-	-	-	-	-	-
45th St. Ent. to FM 2222 Ex.	-	-	-	-	-	-	X
FM 2222 Ex. to FM 2222 Ent.	X	-	-	-	-	-	-
FM 2222 Ent. to Far West Ex.	-	-	X	-	-	X	-
Far West Ex. to Far West Ent.	-	-	-	-	-	-	-
Far West Ent. to Anderson Ex.	-	-	-	X	-	X	-
Anderson Ex. to Steck Ex.	X	-	-	-	-	-	-
Steck Ex. to US 183 Ex.	-	-	-	-	-	-	-
US 183 Ex. to US 183 Ex. (2 lane)	-	-	-	-	-	-	-

Table Legend

X = Theoretical presence of a bottleneck due to a particular criterion
X^* = Theoretical presence of a bottleneck due to demand approaching capacity
AM = Morning peak
PM = Evening peak

LANE DROPS FOLLOWING EXIT RAMPS

Bottlenecks often develop where a lane is dropped after an exit. Under heavy flow conditions, bottlenecks form at lane drops because the exiting demand is too low to reduce the main lane demand below the capacity of the reduced freeway section immediately downstream of the lane drop. For example, a freeway section has a capacity of 8,000 vph and currently the traffic demand is only at 7,000 vph. A lane drop after an exit lowers the freeway capacity to 6,000 vph. Only 500 vph use the exit ramp, so traffic demand is now 6,500 vph, which is greater than the capacity after the exit ramp. Therefore, a bottleneck will develop at the exit ramp because traffic demand now exceeds the capacity of the upstream freeway section.

Tables 4.3 and 4.4 indicate that there are eight lane drop locations on the southbound Loop 1 study section and seven northbound. Each of these has either already become a bottleneck or is likely to become one as demand grows and changes. The only practical solution to a lane-drop bottleneck is extension of the dropped lane beyond the exit. As indicated in Tables 4.3 and 4.4, the number of lanes decreases eight times but it also increases eight times along the 11-mile section. Provision of a minimum 12 foot wide full-depth paved right-side shoulder from each lane-drop location to the next location where the number of lanes increases would provide operational flexibility needed to treat lane-drop-induced bottlenecks. This leads to **operational flexibility concept number 1**: **Provide minimum 12 foot wide full-depth paved right-side shoulder from each lane-drop location to the next lane-number transition or for at least 2,500 feet.**

DEMAND EXCEEDING CAPACITY DOWNSTREAM OF AN ENTRANCE RAMP

In addition to lane-drop locations, bottlenecks occur where traffic demand on a freeway section exceeds the capacity. This situation can occur immediately following any entrance ramp where the acceleration lane associated with the ramp does not become a basic freeway lane. Tables 4.5 and 4.6 identify nine northbound Loop 1 locations where this situation is currently problematic, along with five southbound locations within the 11-mile case study section. At these locations, the main-lane traffic demand is near capacity and an entrance ramp permits enough additional traffic to force the section demand above the capacity, resulting in a bottleneck. In addition, Tables 1 and 2 in the appendix compare the freeway capacity to the morning and evening main lane demands for the northbound and southbound directions.

Two possible solutions might be suggested for such situations. One approach would reduce demand allowed to enter the freeway using the problematic ramp through ramp metering or provision of route-guidance information to motorists. This approach can be effective under certain conditions in which alternative routes are available and acceptable. The other approach would provide for future re-striping of the freeway section, adding a lane downstream of the entrance ramp through provision of a minimum of 12 foot wide full-depth paved, right-side shoulder from the entrance ramp acceleration lane end to the next entrance ramp. This leads to **operational flexibility concept number 2: Provide a minimum 12 foot wide full-depth paved, right-side shoulder from each entrance ramp acceleration lane end to the next exit ramp.**

WEAVING SECTIONS

Weaving sections are freeway sections where an auxiliary lane begins at an entrance ramp and ends at an exit ramp. In these sections, drivers perform weaving maneuvers to enter or exit the freeway. For instance, drivers entering the freeway need to merge from the auxiliary lane to the main lanes while exiting drivers need to merge from the main lanes to the auxiliary lane. In weaving sections of less than 2,700 feet, these maneuvers reduce the capacity of the section and under heavy main lane and ramp-flow conditions the weaving section will begin to breakdown and become a bottleneck.

To determine the presence of weaving-induced bottlenecks, a weaving analysis was performed for Loop 1 weaving sections using the methods of the Highway Capacity Manual. The analysis provides a level of service (LOS) for the weaving and non-weaving maneuvers. If these maneuvers have an LOS of D or worse, then it is likely that the analyzed weaving section is a bottleneck. Tables 4.7 and 4.8 below illustrate the LOS results for southbound and northbound weaving sections of Loop 1. Based on the calculated LOS, X's in the weaving column of Tables 4.5 and 4.6 compare the possible presence of a weaving-induced bottleneck to the observed areas of congestion and the X's identify three problematic weaving sections. Finally, Tables 5 and 6 in the appendix show the weaving analysis methods and calculations.

One solution to weaving-section congestion is the use of ramp metering to reduce the entrance-ramp flow coming into the section. According to the 1997 Highway Capacity Manual, increasing the weaving section length to more than 2,500 feet would essentially remove any weaving effects. Therefore, an excellent design concept is to maximize the distance between entrance and exit ramps, which signify the beginning and end of the section. However, owing to existing street geometry and to many other common constraints, particularly for an existing freeway like the Loop 1 case study section, this may not be practical. A more practical solution to weaving area congestion is the addition of another freeway through lane within the weaving area. An additional through lane will supplement section capacity by providing more gaps for entering traffic and by potentially easing the weaving process. Because an additional lane cannot be easily added to the freeway right side, the left side becomes the logical place for the supplementary lane. This leads to **operational flexibility concept number 3: At least 1,500 feet before and after weaving sections, provide a minimum 12 foot wide full- depth paved, left-side shoulder.**

This shoulder provision will permit re-striping when bottleneck problems demand a weaving section modification. If a facility is being designed with 12 foot left shoulders in the vicinity of weaving sections, this width might be increased to 20 feet, allowing for an 8 foot shoulder during the time that the additional weaving capacity requires use of the additional left lane.

Table 4.7 Weaving Analysis of Southbound Weaving Sections

Freeway Section			Weaving	Non-Weaving
Entrance	Exit	Peak Hour	LOS	LOS
US 183	Steck	8:00-9:00	F	F
Steck	Far West	8:00-9:00	D	D
45th	35th	8:00-9:00	C	C
35th	Westover	8:00-9:00	D	C
Westover	Windsor	8:00-9:00	C	B

Table 4.8 Weaving Analysis of Northbound Weaving Sections

Freeway Section			Weaving	Non-Weaving
Entrance	Exit	Peak Hour	LOS	LOS
Enfield	Windsor	4:30-5:30	C	C
Windsor	Westover	5:00-6:00	C	C
Westover	Windsor	5:00-6:00	B	B
Far West	West Anderson	5:00-6:00	E	D

ACCELERATION LENGTHS

Entrance ramp acceleration-lane lengths are very important for uninterrupted flow on freeway sections. Inadequate or short acceleration-lane lengths do not allow entrance-ramp vehicles enough time or space to find suitable gaps required to merge safely and smoothly into the main lanes. Furthermore, when short acceleration-lane lengths combine with near capacity main lane flow, gaps become more difficult to find and friction between main lane and ramp vehicles increases. As a result, freeway operations deteriorate and bottleneck forms at the entrance ramp.

To avoid this situation AASHTO developed design guidelines for minimum acceleration-lane lengths for one-lane entrance ramps, based on the average speed of vehicles using a ramp and the freeway design speed. According to Tables 4.5 and 4.6, three southbound entry ramps and one northbound ramp do not meet AASHTO criteria. Clearly, if one were designing a new or remodeled freeway, she (he) would design adequate ramp facilities. However, over time, design specifications change in response to many external influences, not the least of which is vehicle characteristics. Therefore, a new or remodeled ramp may meet design standards when designed, but may become inadequate during its working life. This is another reason for implementing operational flexibility concept number 2: **Provide a minimum 12 foot wide full-depth paved, right-side shoulder from each entrance ramp acceleration-lane end to the next exit ramp.**

This concept will provide a means of increasing the acceleration-lane length through re-striping if, or when, it becomes necessary. Provision of the right-of-way and shoulder will also prove beneficial for incident management, as indicted in Chapter 3.

ON-SITE OBSERVATIONS

To confirm the presence of bottlenecks for the previous criteria, observers drove on LOOP 1 several times during peak periods. The following observations were made for both southbound and northbound directions of Loop 1.

SOUTHBOUND MORNING PEAK

Heavy volume on the US 183 entrance, combined with a significant number of weaving maneuvers, causes a bottleneck at the freeway section from the US 183 entrance to the Steck exit.

A short acceleration lane at the West Anderson entrance hinders the ability of ramp vehicles to merge smoothly into the main lanes. Also, the heavy main lane demand further hinders merging because the main lanes are full. As a result, entering vehicles have a difficult time finding gaps to merge into the main lanes. Consequently, ramp vehicles slow down, which in turn forces the main lanes to slow down to allow ramp vehicles to merge into the traffic flow.

The same situation described for the West Anderson entrance occurs at the Far West entrance. Unfortunately, the situation is worse because Far West is only 2,110 feet downstream of West Anderson. So, operations at West Anderson impact operations at Far West because vehicles entering at West Anderson fill the right lane, closing any gaps for vehicles entering at Far West. Thus, the effect of West Anderson operations on Far West operations, plus their short acceleration lanes, causes this section of Loop 1 to be a bottleneck.

At the FM 2222 entrance ramp, poor merging operations on the ramp and the under-utilization of an existing auxiliary lane cause minor disturbances in the main lane traffic flow. On the FM 2222 entrance, two lanes merge into one before the start of the auxiliary lane. Under heavy demand conditions, poor ramp merging operations cause vehicles to enter the auxiliary lane at a slow speed. These vehicles tend to not use the auxiliary lane to increase their speed; instead, they immediately try to merge into the main lanes. As a result, right-lane vehicles are forced to slow or to quickly move from the right freeway lane, these sudden maneuvers cause the flow conditions to break down.

Finally, after the 45th Street exit, freeway speeds improve and remain high until vehicles reach the river. As expected, there are no traffic flow problems south of the river during the morning peak.

SOUTHBOUND EVENING PEAK

Just south of the river from the 1st, 5th, and Lake Austin entrance to the Bee Caves exit there is some minor congestion in the two right-most lanes. Heavy ramp volumes at both the entrance and the exit, combined with a significant number of weaving maneuvers, interrupt free flow conditions at this location.

A major bottleneck occurs south of the river at the Loop 360 exit. At this exit the freeway drops a lane, thereby reducing the freeway capacity to only two lanes after the exit. Unfortunately, the exiting demand is too small to compensate for the loss of capacity caused by the lane drop. As a result, main lane demand exceeds the capacity and a bottleneck forms at the exit.

NORTHBOUND MORNING PEAK

The regularly occurring observed traffic problems occur south of the river at the US 290/Southwest Parkway entrance, the SH 360 entrance, and at the river bridge. On typical mornings, vehicle speeds reach no more than 15 mph from the SH 360 entrance to the river.

NORTHBOUND EVENING PEAK

Just north of the river, major congestion exists from the 1st & 6th Street entrance to the 35th Street entrance. The congestion eases after the 35th Street entrance but some minor congestion occurs at the FM 2222 exit. After the FM 2222 exit, traffic continues at free flow speeds through the US 183/Loop 1 interchange.

The congestion from the 1st & 6th Street entrance to the 35th Street entrance is the worst seen anywhere at any time on Loop 1. Very heavy traffic volumes using the 1st and 6th Street entrance form long queues on the ramp and literally “flood” the freeway main lanes. In addition, weaving sections from the Enfield entry to Windsor exit, Windsor to Westover, and Westover to 35th never let speeds recover from the massive influx of vehicles entering at the 1st and 6th Street entrance.

Just as speeds are beginning to improve, a short acceleration lane at the 35th Street entrance hinders smooth merging into the main lanes. After the 35th Street exit, speeds steadily improve until the FM 2222 exit, where friction between exiting and main lane vehicles reduces freeway speeds.

RECOMMENDED BOTTLENECK SECTION IMPROVEMENTS

The freeway sections chosen for bottleneck improvement evaluation (considering the potential impact of operational flexibility concepts) are listed below.

- Southbound direction West Anderson entrance ramp to the FM 2222 exit ramp
- Southbound direction Loop 360 exit ramp
- Northbound direction 1st and 6th Street entrance ramp
- Northbound direction 35th Street entrance ramp

WEST ANDERSON ENTRANCE RAMP TO THE FM 2222 EXIT RAMP

On southbound Loop 1, the Far West entrance ramp is only 2,080 feet downstream of the West Anderson entrance ramp. High traffic demand, the short distance between the ramps, and insufficient acceleration lengths for these ramps all contribute to congestion on this section during the morning peak.

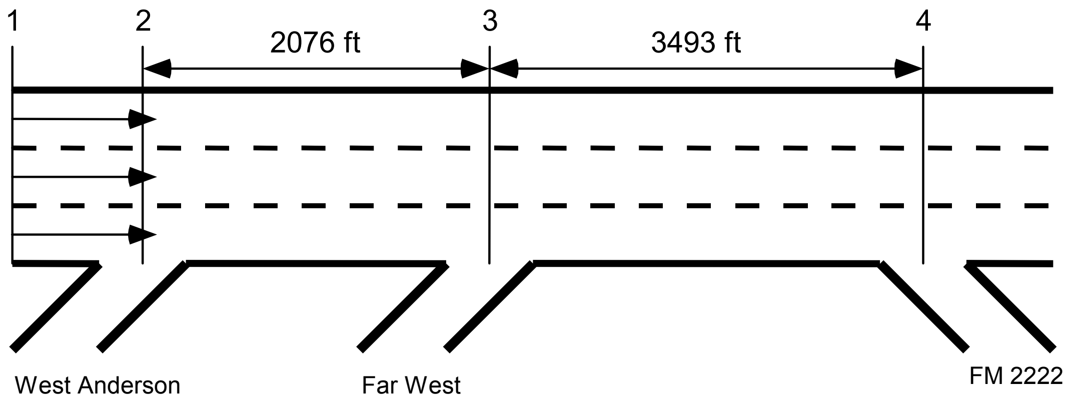

Figure 4.1 West Anderson Entrance to FM 2222 Exit

One potential solution to this bottleneck is to make improvements to the acceleration lanes for both the West Anderson and Far West ramps. Table 4.9 describes the configuration of these entrance ramps, including their existing acceleration lane lengths and the minimum required and recommended acceleration lane lengths. The minimum required acceleration-lane length depends on the speed of the vehicles using the ramp and on the freeway-design speed. The recommended length is the AASHTO desirable acceleration-lane length when ramp and freeway volumes are approximately equal to the design merging area capacity.

Vehicles on these ramps have an approximate average speed of 38 mph, while the design speed of Loop 1 is 70 mph. Therefore, based on AASHTO guidelines, the required minimum acceleration lane length is 640 feet. However, ramp and freeway volumes are approximately equal to the design capacity of the merging area, so the acceleration lanes should be at least 1,300 feet. At Far West, there is adequate space to lengthen the acceleration lane. On the other hand, constructing a 1,300 foot acceleration lane at West Anderson is not possible because it would interfere with merging operations at the Far West entrance. Therefore, increasing the distance separating these ramps will be necessary.

Table 4.9 Acceleration Lane Lengths for West Anderson and Far West Ramps

Description of the ramp	Nature of Ramp	Acceleration length (m) Existing	Required	Recommended
West Anderson entrance ramp	Tapered	193.3	193.3	400
Far West entrance ramp	Parallel	156	193.3	400

A FRESIM analysis of before and after implementation of greater acceleration-lane lengths showed little improvement to freeway operating speeds. Table 4.10 compares freeway speeds during the morning peak, before and after implementing of the improvements. Each link represents a freeway segment between two section lines in Figure 4.1.

Table 4.10 FRESIM Analysis of Freeway Speeds

	Existing Conditions Speed (km/h)			After Improvements Speed (km/h)		
Time Periods	Link (1,2)	Link (2,3)	Link (3,4)	Link (1,2)	Link (2,3)	Link (3,4)
7:00-7:15	96	81.6	75.2	96	83.2	78.4
7:15-7:30	84.8	62.4	64	83.2	62.4	67.2
7:30-7:45	84.8	59.2	60.8	84.8	60.8	64
7:45-8:00	88	64	65.6	86.4	65.6	67.2
8:00-8:15	88	60.8	62.4	88	60.8	64
8:15-8:30	60.8	51.2	59.2	60.8	51.2	60.8
8:30-8:45	49.6	48	57.6	49.6	48	59.2
8:45-9:00	43.2	46.4	56	44.8	48	59.2

Increasing the distance between the ramps allows for a slight variation of the improvements discussed above. To increase the distance, the West Anderson ramp could be moved north, with improvements still made to its acceleration lane, and the Far West ramp could be moved south. Instead of improving Far West's acceleration lane, the merge condition could be eliminated by adding an auxiliary lane from Far West to the FM 2222 exit (Figure 4.2). Currently, nearly 3,500 feet separate the Far West and FM 2222 ramps, so care must be taken to ensure that the weaving maneuvers, created by the auxiliary lane, do not severely impact traffic flow through this section. Table 4.3 displays the results of a weaving analysis and the effect auxiliary-lane length has on freeway speeds and level of service. Based on the weaving analysis for traffic volumes from 8:00 to 9:00 am, an auxiliary lane of at least 2,190 feet will provide adequate speeds and LOS. Also, this analysis shows that speeds between the Far West and FM 2222 ramps, Link (3,4), of Table 4.10, are greater with an auxiliary lane than with a longer acceleration lane at Far West.

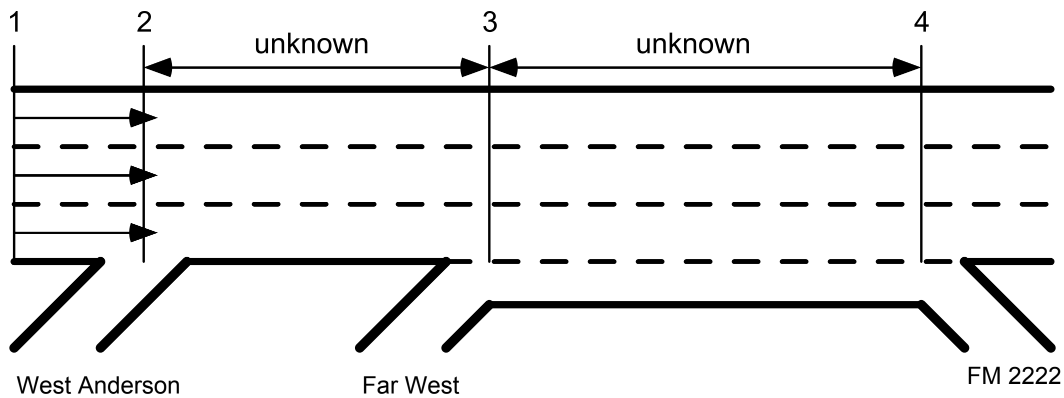

Figure 4.2 Auxiliary Lane from Far West to FM 2222

Table 4.11 Speeds and LOS Based on Different Auxiliary Lane Lengths

Auxiliary Lane Length (m)	Weaving Speeds (km/h)	Non-Weaving Speeds (km/h)	Weaving LOS	Non-Weaving LOS
333.3	59.5	72.4	E	D
400	62.75	75.6	E	D
466.7	65.97	77.2	D	C
533.3	69.2	78.8	D	C
600	70.8	78.8	D	C
666.67	72.4	80.45	C	C
733.3	74	82	C	C
800	75.6	82	C	C
866.67	77.2	83.67	C	C

LOOP 360 EXIT RAMP

During weekday evening peak periods, in the southbound direction, a lane drop at the exit ramp to westbound Loop 360 (Barton Creek Mall exit) causes a severe bottleneck. Figure 4.3 shows why a bottleneck forms. Before the Loop 360 exit, the capacity, c_1, is greater than the traffic demand, v_1. A lane drop at the Loop 360 exit reduces the capacity of the freeway to c_2, but only approximately 450 vehicles exit the freeway. As a result, because traffic demand after the Loop 360 exit, v_3, is greater than the capacity after the exit, c_2, a bottleneck forms.

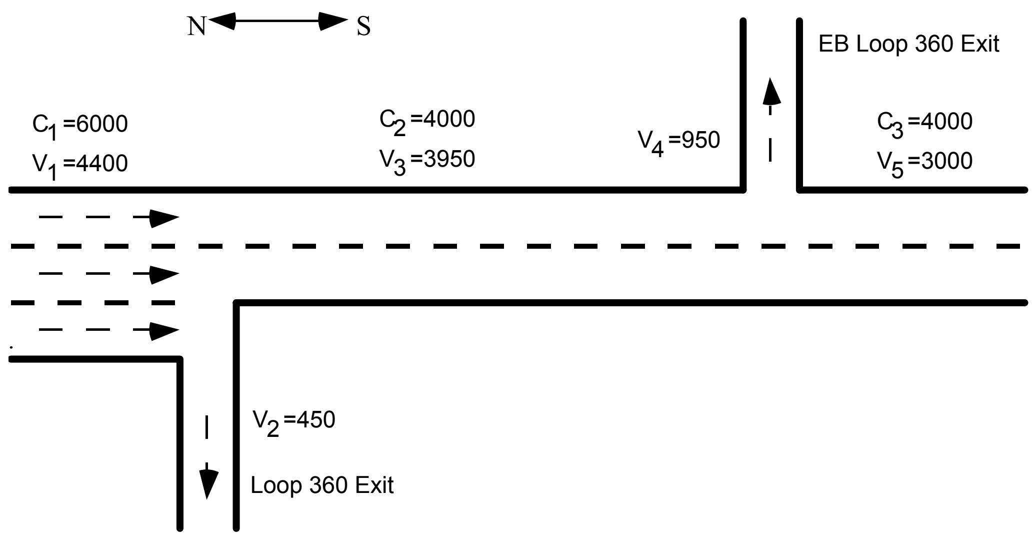

Figure 4.3 Schematic of the Current Conditions for Southbound Loop 1 from Westbound Loop 360 Exit to Eastbound Loop 360 Exit Showing Ramp and Main Lane Volumes

Eliminating this bottleneck requires removing the lane drop at the Loop 360 exit by adding a third lane up to the EB Loop 360 exit. This third lane increases the capacity, c_2, thus making it greater than v_3 and eliminating the bottleneck. Right-of-way constraints force the additional lane to be dropped after the eastbound Loop 360 exit, but this should not create a new bottleneck because the capacity, c_3, is greater than the traffic demand, v_5. In addition, a FREQ analysis showed that approximately 390 vehicle hours of travel time per peak period on the main lanes could be saved by this lane addition. Figure 4.4 illustrates the new freeway alignment.

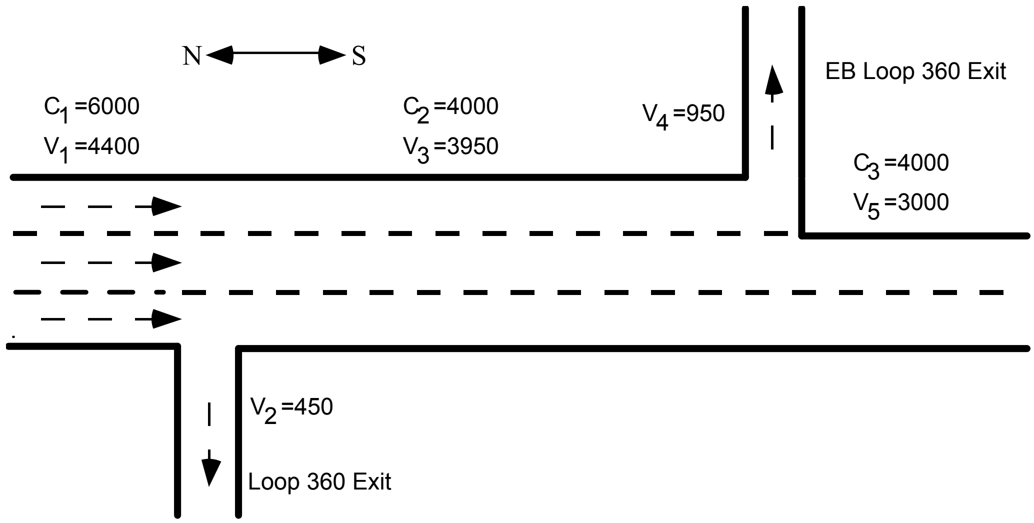

Figure 4.4 Schematic of the Proposed Solution to Eliminate the Bottleneck at the Westbound Loop 360

There are two options as regards adding another lane in this section. Currently, the pavement is 47 feet wide, so this section could be re-striped with three 12 foot lanes and 2 foot shoulders on either side. The other option is to add 12 feet to the pavement width and stripe the section with three 12 feet and 12 feet and 4 feet shoulders on the right side and left side, respectively. The right-hand side shoulder would have to be dropped before the 360 overpass because the bridge piers restrict the right-of-way.

1ST AND 6TH STREET ENTRANCE RAMP

In the northbound direction, during the evening peak period, congestion develops north from the 1st and 6th Street entrance ramp to the 35th Street exit. The cumulative effects of high volumes using the 1st and 6th Street and Enfield entrance ramps, along with the lane drop at the Windsor exit, create one of the worst Loop 1 bottlenecks. Extensive study and many observations of this bottleneck have led to the conclusion that the heavy volume on the 1st and 6th Street entrance ramp is the catalyst for the traffic flow problems. The addition of at least one lane beyond the end of the entrance ramp merge-acceleration area would be the best solution. However, lack of available shoulders or right-of-way essentially eliminates this possibility. By regulating the volume entering the freeway through ramp metering, the bottleneck can be eliminated.

The freeway simulation software, FREQ, was used to evaluate the effectiveness of metering the 1st and 6th Street entrance ramp. These analyses indicate a maximum allowable ramp entry rate of 1,400 vph would allow freeway speeds to remain above 50 mph. Current ramp flows exceed 1,400 vph, metering without diversion of some ramp traffic to other times or routes would cause large ramp delays. Table 4.12 displays results from a FREQ simulation, which indicate roughly 1,300 vehicles would need to be diverted to other routes or times during a 3-hour analysis period from 16:00 to 19:00 hrs. Alternate northbound paths along Lamar Blvd. and Burnet Road are feasible.

Table 4.12 Number of Diverted Vehicles Based on a Metering Rate of 1,400 vph

	Ramp Delay After Metering Assuming No Vehicles Diverted (veh-hr)	Ramp Delay Assuming Vehicles Diverted (veh-hr)	Ramo Delay Decrease (veh-hr)	Current Demand on 6th st. Ramp	Number of Diverted Vehicles
16:00	14	0	14	465	115
16:15	50	1	49	522	172
16:30	99	12	87	517	167
16:45	145	20	125	503	153
17:00	181	23	158	467	117
17:15	205	27	178	399	49
17:30	219	25	194	425	75
17:45	235	22	213	423	73
18:00	263	25	238	502	152
18:15	296	28	268	461	111
18:30	317	28	289	407	57
18:45	328	29	299	380	30
			2112		1271

Figure 2, of the appendix, compares the speed contour diagrams of the main lanes before and after metering. Table 4.13, compares the freeway travel times before and after metering and shows that metering could save an estimated 188 vehicle hours per day of freeway travel time.

Table 4.13 FREQ11 Estimates for Freeway Travel Time and Speed Before and After Metering

	Before Metering		After Metering		Freeway
	Freeway		Freeway		Travel Time
	Travel Time	Speed	Travel Time	Speed	Savings
Time	(veh-hr)	(km/hr)	(veh-hr)	(km/hr)	(veh-hr)
16:00	157	91.4	154	91.8	3
16:15	162	89.3	156	91.5	6
16:30	185	80.2	172	86.1	13
16:45	193	76.5	162	89.8	31
17:00	213	71.8	182	84.0	31
17:15	210	69.6	160	88.8	50
17:30	185	79.2	154	91.7	31
17:45	158	90.1	153	92.0	5
18:00	164	86.9	156	90.4	8
18:15	156	89.4	149	92.2	7
18:30	143	92.6	142	92.8	1
18:45	143	92.6	141	92.8	2
					188

35TH STREET ENTRANCE RAMP

Like the West Anderson and Far West entrance ramps, the 35th Street entrance ramp is not up to design standards. The acceleration-lane length is inadequate in providing enough time to accelerate and merge into the main lanes, especially during the evening peak hour when ramp and freeway volumes are approaching the merging-area design capacity. Table 4.14 shows the nature of the entrance ramp, as well as the existing and minimum required acceleration-lane lengths. Vehicles on this ramp have an approximate average speed of 30 mph and the design speed of Loop 1 is 70 mph; therefore, based on AASHTO guidelines the required minimum acceleration lane length is 1,345 ft.

Table 4.14 Acceleration Lane Lengths for 35th Street Entrance Ramp

Description of the ramp	Nature of Ramp	Acceleration length (ft)	
		Existing	Required
35 th Street entrance ramp	Parallel	830	1345

SOUTHBOUND ENFIELD ENTRANCE

To ease southbound congestion on the Town Lake Bridge during the evening peak, TxDOT proposes to eliminate the lane drop at the 1st and 5th Street exit and change the Enfield entrance to a merge condition. Figures 4.5 and 4.6 show the current and proposed geometric conditions, respectively. Through a careful study of the proposed changes potential advantages and disadvantages were identified.

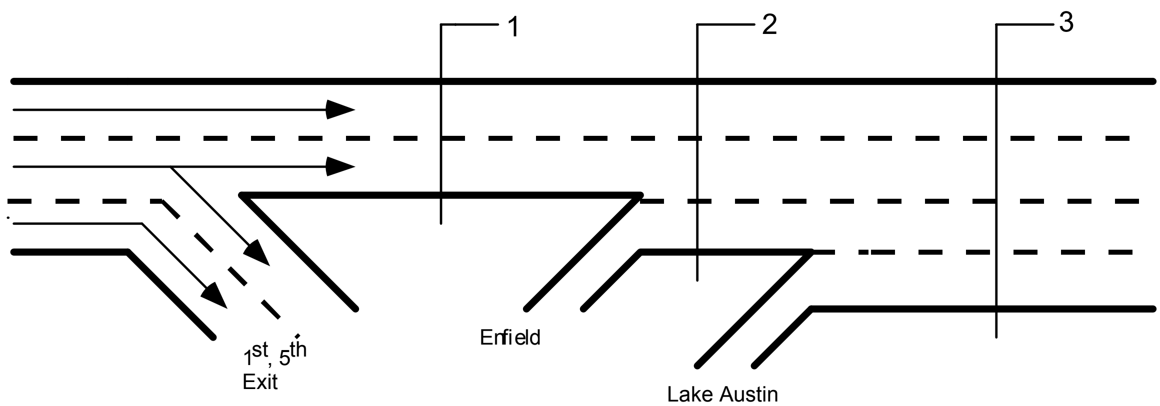

Figure 4.5 Current Conditions

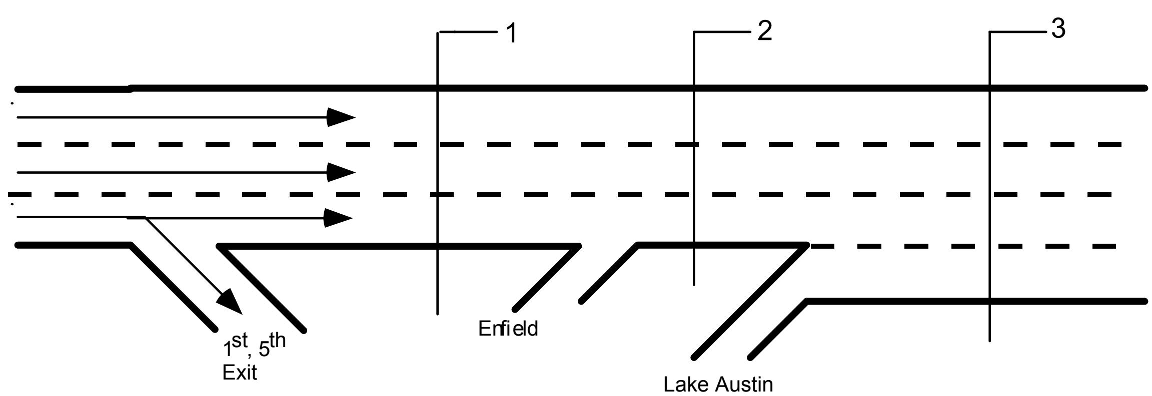

Figure 4.6 Enfield Change to a Merge Condition

The proposed configuration provides the following advantages:

- Eliminates a weaving movement;

  Adding a third lane to sections 1 and 2 enables main lane vehicles wishing to exit at Bee Caves to make only one weaving movement instead of two.

- Meters indirectly the Enfield entrance;

  When the right-most main lane is near capacity the entry rate for ramp vehicles decreases because it is difficult for ramp vehicles to find a suitable gap to merge into the main lanes.

- Allows through traffic to avoid weaving vehicles;

  Adding a third lane to sections 1 and 2 allows two lanes, instead of one, to be dedicated to vehicles not exiting at Bee Caves. This addition should help ease congestion for vehicles whose destinations are exits downstream of Bee Caves.

The proposed configuration provides the following disadvantages:

- Rear-end collisions;

  Rear-end collisions could increase on the Enfield entrance when the far-right main lane is near capacity and ramp vehicles are forced to slow down or even stop before they merge into the main lanes.

- Shoulder loss;

  At the Enfield entrance the bridge is only 61 feet wide. Three 12 foot main lanes and a 12 foot acceleration lane will leave only 13 feet to be shared between both left and right shoulders.

TRAFFIC VOLUME CONSIDERATIONS

Table 4.15 shows 15-minute traffic volumes for sections 1, 2 and 3 as shown in Figures 4.5 and 4.6. Currently, these traffic volumes are well below the capacities of these freeway sections; therefore, an increase in capacity is currently not necessary. In addition, a FREQ analysis of before and after implementation, using current traffic demand, showed no improvement in freeway operations.

As traffic volumes increase, the combined effects of increasing capacity and the indirect metering of the Enfield entrance could potentially alleviate future bottlenecks. In the future, if drivers know main lanes will be full and gaps difficult to find, they will become accustomed to ramp vehicles that slow down or stop before they merge into the main lanes, the result of which could be a reduction in rear-end collisions. In the meantime, rear-end collisions could be a problem because ramp vehicles will not be expecting other ramp vehicles to slow down or stop before merging into the main lanes.

Table 4.15 Freeway and Entrance Ramp 15-Minute Traffic Volumes

	15-minute Traffic Volumes (PM)				
Time	Section 1	Enfield Ent.	Section 2	Lake Austin	Section 3
16:00	739	183	922	345	1267
16:15	868	215	1083	284	1367
16:30	776	244	1020	271	1291
16:45	723	307	1030	329	1359
17:00	814	266	1080	322	1402
17:15	571	304	875	430	1305
17:30	780	313	1093	277	1370
17:45	796	274	1070	269	1339
18:00	695	200	895	365	1260
18:15	708	181	889	361	1250
18:30	680	162	842	339	1181
18:45	696	125	821	336	1157

Based on the ideas presented in the previous sections, the following improvements were recommended.

LOOP 360/BARTON CREEK MALL EXIT TO EASTBOUND LOOP 360 EXIT

This improvement was implemented and significantly improved traffic flow for southbound Loop 1 during the evening peak. The additional lane provided the extra capacity needed at this location at a minimal cost.

The key geometric feature that enabled implementation of this improvement was a 12 foot right-side shoulder that had been originally provided between these two exits. Therefore, re-striping it as a regular travel lane was a fairly simple matter. This implementation provides partial validation of operational flexibility concept number 1: **Provide minimum**

12 foot wide full-depth paved, right-side shoulder from each lane-drop location to the next lane-number transition or for at least 2,500 feet.

SOUTHBOUND WEST ANDERSON ENTRANCE RAMP TO FM 2222 EXIT

Improvements to the southbound section from the West Anderson entrance to FM 2222 were proposed to help improve morning traffic flow problems caused by the current geometric conditions. During periods of heavy demand, a longer acceleration lane at West Anderson would give ramp vehicles more time to find a suitable gap in the traffic stream. The greater distance between the West Anderson and Far West ramps reduces the effect that West Anderson operations have on Far West operations and allows for implementing the West Anderson improved acceleration lane. In addition, adequate space is available to move these ramps north and south, respectively, of their current location. Finally, the auxiliary lane from Far West to FM 2222 replaces the merge condition at Far West with weaving maneuvers, which have less impact on main lane traffic flow. Because this segment includes a weaving section and the improvement involves adding a weaving section lane, operational flexibility concept number 3; **at least 1,500 feet before and after weaving sections, provide a minimum 12 foot wide full-depth paved, left-side shoulder,** would greatly simplify implementation. This section analysis is thus an example of a bottleneck solution implementation made easy through potential implementation of operational flexibility concept number 3.

NORTHBOUND 1ST AND 6TH STREET ENTRANCE

The very heavy traffic demand at the 1st and 6th Street entrance is the major factor contributing to the severe congestion at this entrance to the 35th Street exit. As noted previously, the addition of a lane and/or extension of a lane through the section is not easily done owing to right-of-way constraints and to lack of shoulders that could be re-striped. The problem at this location provides an example of a situation where operational flexibility concept number 2 could greatly simplify a solution: **Provide a minimum 12 foot wide full-depth paved, right-side shoulder from each entrance ramp acceleration-lane end to the next exit ramp.**

Metering this demand limits the vehicles entering the freeway, thus improving freeway speeds. However, metering is not a perfect solution. The high ramp demand will cause long queues to form behind the ramp meters. Although the freeway main lanes will benefit from this plan, the increase in delay incurred by ramp vehicles will encourage drivers to seek alternative routes. An examination of alternative route availability generally indicated that sufficient capacity was not available.

LENGTHEN ACCELERATION LANE OF 35TH STREET ENTRANCE RAMP

Increasing the acceleration lane to 1,344 feet at the 35th Street entrance will improve merging operations and will help increase main lane speeds. This recommended improvement could also be eased into implementation if operational flexibility concept number 2 had been incorporated into the ramp design: **Provide a minimum 12 foot wide full-depth paved, right-side shoulder from each entrance ramp acceleration lane end to the next exit ramp.**

Southbound Enfield Entrance

Although this potential bottleneck improvement was not recommended or implemented, operational flexibility concept number 3, **at least 1,500 feet before and after weaving sections, provide a minimum 12 foot wide full-depth paved, left-side shoulder**, would permit easier implementation or a different, better solution.

SUMMARY

More often than not, relieving a bottleneck at one location will move the bottleneck to a new downstream location. An upstream bottleneck restricts traffic flow, thereby reducing the demand on downstream freeway sections; but eliminating the upstream bottleneck releases the formally restricted traffic flow to downstream freeway sections. When a downstream freeway section has inadequate capacity to handle this influx of demand, a bottleneck forms.

One way to predict where a new downstream bottleneck might form is to compare the potential of the derived freeway-section demand to the capacity. If the derived demand of a freeway section, or sections, known to be downstream of an observed bottleneck is greater than the capacity and there is not an observable bottleneck at the freeway section, a bottleneck will form when the upstream bottleneck is removed.

On southbound Loop 1, north of the river, the situation described above may be very likely to happen. Eliminating the bottleneck at West Anderson and Far West will move the bottleneck south to the 45th Street exit or to the Westover exit. In the northbound direction, a particular bottleneck is difficult to pinpoint because of the massive congestion occurring at the 1st and 6th Street entrance to the 35th Street entrance. Ramp metering at the 1st and 6th Street entrance and an improved acceleration lane at the 35th Street exit should clear up the congestion and will probably cause the bottleneck to move to the vicinity of the FM 2222 entrance. Southbound, south of the river, capacity downstream of the Loop 360 exit can handle extra demand once the bottleneck is eliminated at the Loop 360 exit.

Provision of the operational flexibility design concepts would provide the freeway operators with needed flexibility to add and remove capacity in response to changes in freeway demand and operational conditions. As indicated in the previous sections, these simple concepts could greatly simplify implementation of a wide range of bottleneck solutions.

CHAPTER 5 SUMMARY

The previous four chapters have presented an introduction to the operational flexibility design concept, a review of freeway congestion mitigation measures, an examination of incident management activities, and a case study of freeway bottleneck treatments. Operational flexibility requirements encompass freeway design measures that would enable effective incident management as well as treatment of bottleneck locations. Because both incidents and bottlenecks are inevitable on urban freeways, design concepts that enable effective treatment of both is highly desirable.

CONGESTION MITIGATION CONCEPTS

Concepts presented in Chapter 2 include seven generic descriptions of freeway congestion mitigation efforts that are being implemented on freeways across the country. These include:

1) High occupancy vehicle (HOV) lanes
2) Freeway ramp metering
3) Lane use restrictions (restricting trucks to specific lanes)
4) High occupancy vehicle (HOV) bypass lanes
5) Improved responses to freeway incidents (incident management)
6) Reduced lane and or shoulder widths
7) Bottleneck mitigation

Implementation of all of these concepts could be simplified through the provision of flexible design concepts. However, incorporating plans for all of them and all subsets of each into a redesigned freeway would be difficult and probably not necessary. A primary objective of the research was to identify those concepts that would most likely be part of congestion mitigation schemes that are implemented. Therefore, incident management and bottleneck mitigation were selected as two congestion mitigation measures that are almost certain to be implemented on virtually all urban freeways. These two concepts are the topics of the two following sections.

INCIDENT MANAGEMENT

Using video surveillance capabilities at the San Antonio and Houston, Texas, traffic control centers, the project team examined a large number of freeway incidents. Detailed characterizations of the incidents, emergency responses, and effects upon freeway traffic were prepared. From this analysis, a clear need for a pathway for emergency vehicles to reach incident sites was identified. Additionally, a clear need for a haven for disabled or damaged vehicles was identified. Such a haven would permit faster incident clearing and a re-opening of main lanes. An obvious solution to both the access path and haven problems is a paved shoulder. This solution led to a recommendation to maintain a minimum 8 foot wide shoulder on at least the freeway right-side for freeways with three or fewer lanes and maintenance of minimum 8 foot wide paved shoulders on both the left and right freeway sides on freeways with more than three lanes per direction.

FREEWAY BOTTLENECKS

A detailed case study of bottleneck sites on the Austin, Texas, Loop 1 freeway was described. The examination of individual bottleneck sites and recommended solutions, some already implemented, led to development of a series of operational flexibility design concepts. These concepts were devised to provide implementation ease for the very typical types of bottleneck solutions proposed for the Loop 1 case study. These concepts are:

<u>Concept number 1</u>: Provide minimum 12-foot-wide, full-depth-paved, right-side shoulder from each lane-drop location to the next lane-number transition or for at least 2,500 feet.

<u>Concept number 2</u>: Provide a minimum 12-foot-wide, full-depth-paved, right-side shoulder from each entrance ramp acceleration-lane end to the next exit ramp.

<u>Concept number 3</u>: At least 1,500 feet before and after weaving sections, provide a minimum 12-foot-wide, full-depth-paved, left-side shoulder.

These concepts imply that, while other congestion mitigation measures are considered and implemented, steps must always be taken to maintain the shoulder room noted. The concepts also imply that, if available, these shoulder spaces will enable bottleneck treatment through lane re-striping, which is much faster and more practically implemented than adding pavement or acquiring right-of-way.

PRIORITIES

An obvious potential conflict exists between the need to maintain continuous shoulders for emergency vehicle paths to incidents and the shoulder reservations for re-striping associated with the operational flexibility design concepts. The two concepts should be considered complementary, rather than mutually exclusive. If the two requirements are simply added together they would produce 20 feet of paved shoulder. However, the intent of the shoulder reservations for lane re-striping is to produce an additional lane through bottleneck sections. Although 12 feet is the normal lane width, significant experience has indicated little loss of operational effectiveness with 11 foot lane widths. The 1994 Highway Capacity Manual suggests a 5 percent reduction in flow potential for 11 foot as opposed to 12 foot lane widths. If all main lanes are re-striped to 11 foot widths through bottleneck sections, then the additional shoulder space required to produce the required additional lane would be substantially less than 12 feet. Table 5.1 shows how the quantity of additional space decreases as the basic number of lanes increases. For example, if a freeway section has three basic lanes, each 12 feet wide, a four-lane section in which all lanes are 11 feet wide can be produced by adding only 8 feet to the basic section.

Table 5.1 Shoulder Width Needed for One Additional Freeway Lane

Lane Widths (feet)			
12		11	
Basic number of lanes	**Available section width (ft)**	**Section width for basic plus one lane (ft)**	**Needed shoulder width (ft)**
2	24	33	**9**
3	36	44	**8**
4	48	55	**7**
5	60	66	**6**
6	72	77	**5**

Therefore, the operational flexibility design concepts might be modified to include only the width necessary to add an additional lane if the basic freeway section is re-stripped to 11 feet lane widths. With this modification, shoulder widths resulting from adding the minimum eight feet emergency vehicle path and the additional lane for re-stripping are not quite as great and are probably more practically implemental.

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APPENDIX A

Accident Photos and Descriptions

Houston

ABBREVIATIONS USED FOR ACCIDENT DESCRIPTION

n/a – not applicable

c – concrete

HOV – high occupancy vehicles lane

S(o), Shl. Out. – outside shoulder

S(m), Shl. Med. – median shoulder

S (op.m.) – median shoulder on opposite direction

Lane 1, etc. – traffic lane number from the median

R (ext.), R(ent.) – exit or entrance ramp

veh. – vehicle(s) involved in the accident

pol. – police vehicles

amb. – ambulance vehicle

fire – fire truck

tow. – towing vehicle

reg.dir.main lanes – regular direction main traffic lanes

shl. – shoulder

opp.dir. main lanes – opposite direction main traffic lanes

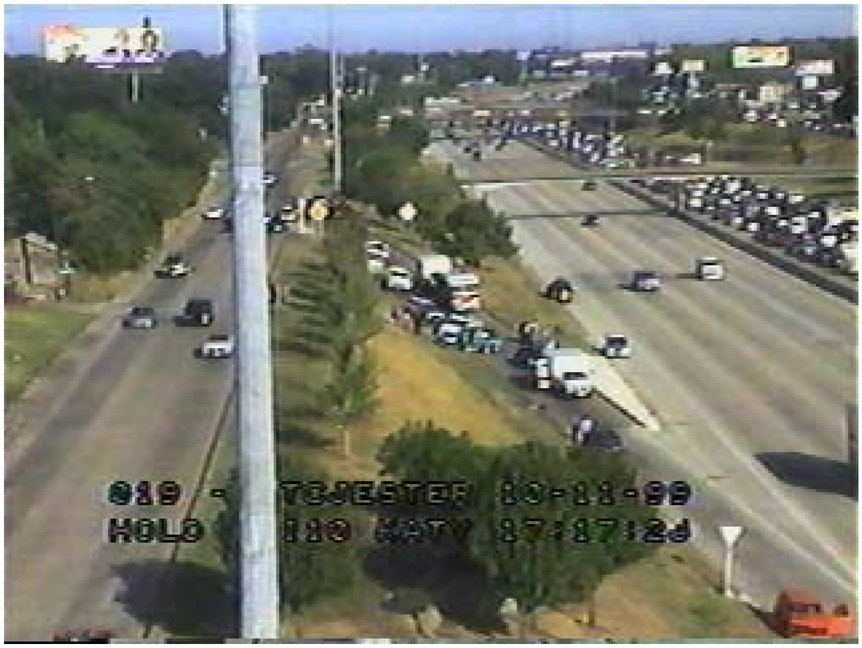
Houston. Accident # 1.

Houston. Accident # 2.

Houston. Accident # 3.

Houston. Accident # 4.

Houston. Accident # 5.



Houston. Accident # 6.

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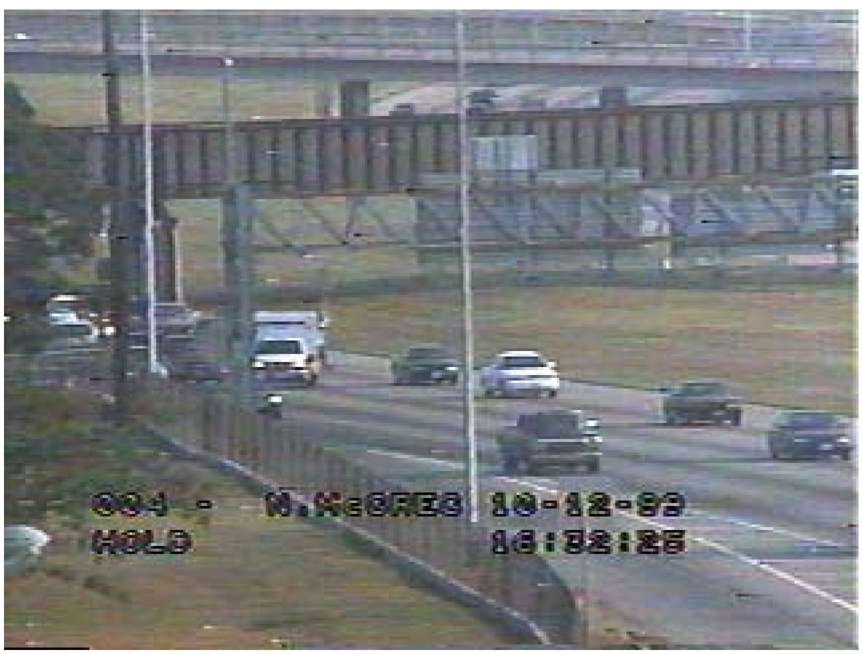
Houston. Accident # 10.

Houston. Accident # 11.

Houston. Accident # 12.



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Houston. Accident # 14.

Houston. Accident # 15.

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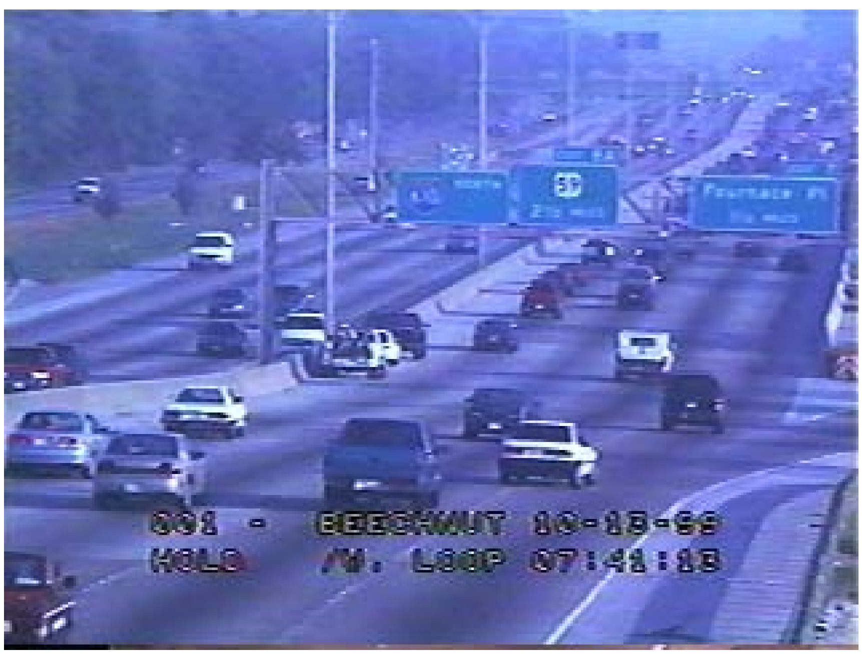

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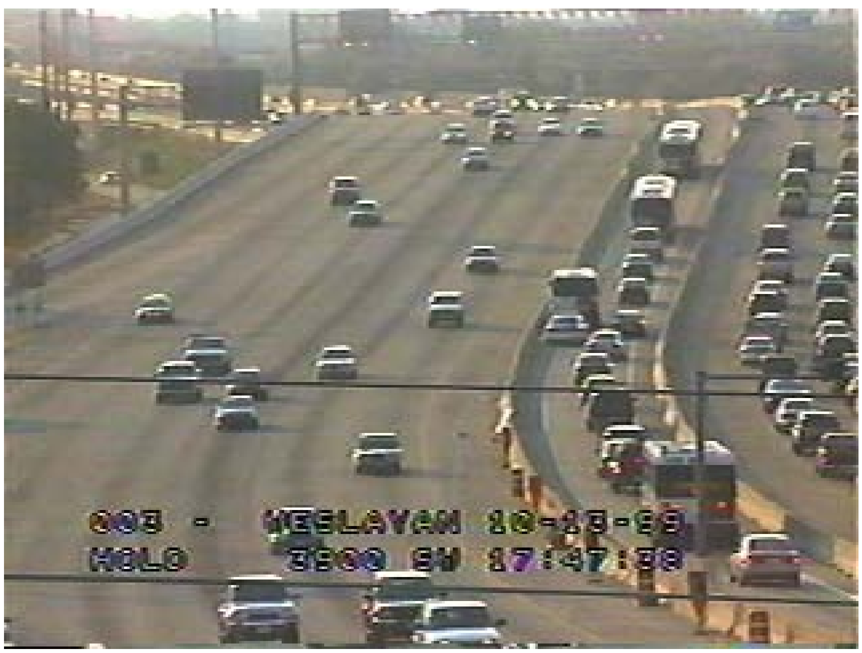

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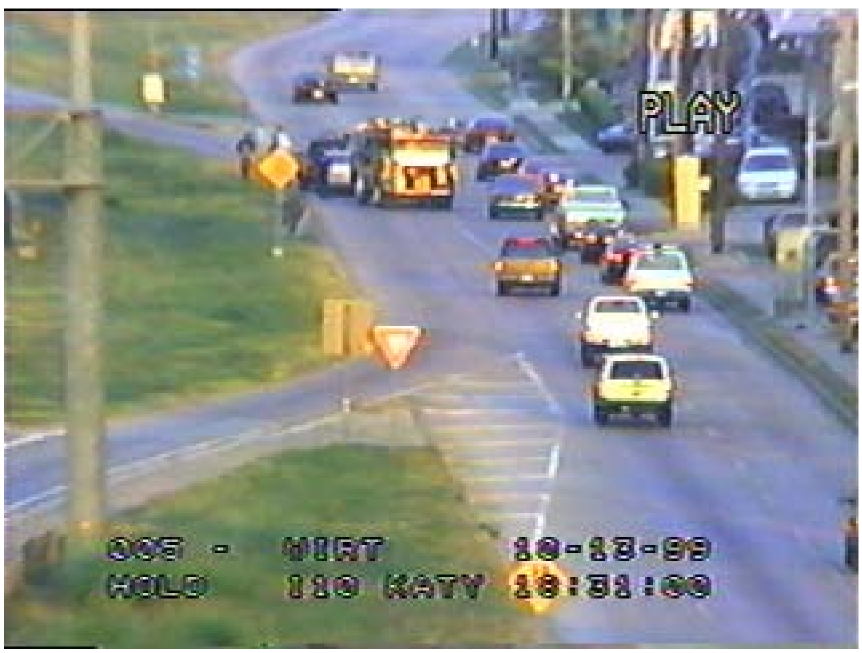

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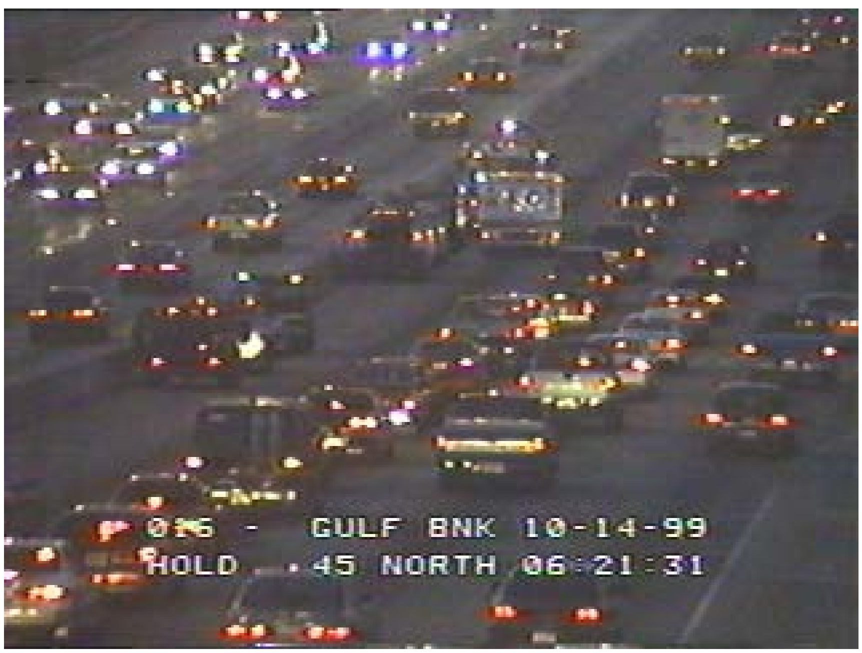
Houston. Accident # 22.



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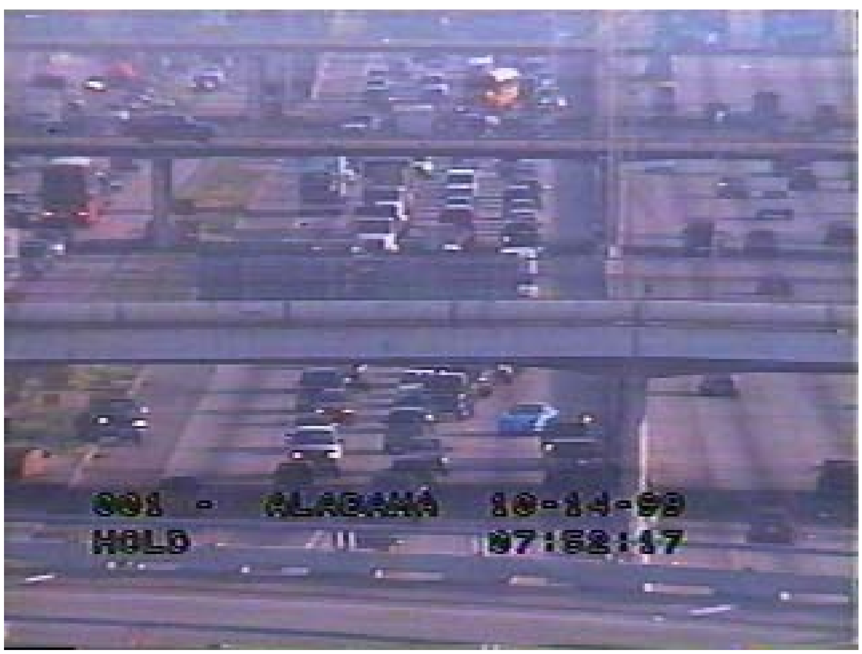
Houston. Accident # 24.



Houston. Accident # 25.

Houston. Accident # 26.

Houston. Accident # 27.

Houston. Accident # 28.

Houston. Accident # 29.

Houston. Accident # 30.

Accident Descriptions: Houston

Appendix A. Accident descriptions. Houston

Accident #	Tape #	Date			Highway	Camera I.D.	Total # of lanes one dir.	Shoulders		Protective bariiers		Start time of recording		Ending time of recording		Lane where accident happened	# of vehicles involved in accident	Blocked lanes when accident happened	Blocked lanes and time of blockage during the accident						Emergency arriving			Notice
		month	day	year				outside	median	outside	median	hr.	min.	hr.	min.				Lane	from hr.	from min.	to hr.	to min.	reason	Way	Time hr.	Time min.	
1	1	10	11	1999	IH 10	13 / ELDRIDGE	3	yes	yes	c	c	15	48	16	6	n/a	2	n/a	S (o)	n/a	n/a	n/a	n/a	veh.,ambul.	n/a	n/a	n/a	traffic normal at the end of recording.
																			S(o)+3	15	48	15	55	ambul.				vehicles: 1 - on shoulder
																			S (o)	15	55	n/a	n/a	veh.				2-out of the road
2	1	10	11	1999	4900 SW	5 / SW SAT	5	yes	yes	no	c	16	2	16	6	n/a	2	n/a	S (o)	n/a	n/a	n/a	n/a	veh., tech.	n/a	n/a	n/a	
3	1	10	11	1999	IH 10	12 / DASFOR	3	yes	yes	c	c	16	19	16	24	1	3	1	1	n/a	n/a	n/a	n/a	veh., pol.				rear-end, lane blocked all recording time
4	1	10	11	1999	45 North	13 / PARKER	1	yes	yes	c	c	15	43	16	39	HOV	1	S	S	n/a	n/a	15	49	veh.	HOV	15	49	technical problem
																			S	15	49	n/a	n/a	veh., tech.				incident on HOV lane
																												minimum influence to traffic
5	1	10	11	1999	IH 10	19 / TCJESTER	1	no	no	no	no	17	5	17	49	on-ramp	5	R	R	n/a	n/a	17	5	veh.,pol.	frontage road	n/a	n/a	accident on the on-ramp
																			R	17	5	17	8	veh.,pol.	main lane	n/a	n/a	
																			R	17	8	17	9	veh.,pol.,fire	frontage road	17	8	
																			R	17	9	17	28	veh.,pol.,fire, ambul.	frontage road	17	9	second ambulance arrived from main lanes
																			R	17	28	17	49	veh.,pol.,tech.				ramp closed for traffic
6	1	10	11	1999	n/a	n/a	4	yes	no	c	c	0	0	0	26	1	1	1	1	n/a	n/a	0	22	veh.	freeway main lanes	0	22	technical problem
																				0	22	0	26	veh.,tech.				time is not real. 0 is recording beginnings
7	1	10	11	1999	n/a	n/a	3	yes	no	no	c	0	0	0	30	3	4	3+S	3+S	n/a	n/a	0	3	veh.	freeway main lanes	0	3	time is not real. 0 is recording beginnings
																			3+S	0	3	0	22	veh.,tech.				3 lanes + entrance/exit ramp
																			S	0	22	n/a	n/a	veh.,tech.				heavy traffic
8	1	10	11	1999	n/a	40 M.P. RR.	5	yes	yes	no	c	17	43	17	47	2	1	2	2	n/a	n/a	17	45	veh.	freeway main lanes	17	45	incident occurred between 17:37 and 17:43
																			S	17	46	n/a	n/a	veh.,tech.				technical problem
9	1	10	12	1999	6200 SW	8 / WESTPARK	6	yes	yes	c	c	7	10	7	28	4	2	4	4	n/a	n/a	7	27	veh.	freeway main lanes	7	27	minor rear-end collision
																			4	7	27	7	28	veh.,pol.				
10	1	10	12	1999	5500 SW	7 / CHIMROCK	6	yes	yes	c	c	15	27	15	48	n/a	2	n/a	S (m)	n/a	n/a	15	48	veh.,pol.,tech.	n/a	n/a	n/a	no influence on main traffic
																									freeway main lanes	15	40	
11	1	10	12	1999	n/a	22 / STOKES	2	yes	yes	no	c	15	21	15	44	1	2	1+S(o)	1+S(m)	n/a	n/a	15	24	veh.				looks like a freeway intersection
																			1+S(m)	15	24	15	43	veh.,pol.	main lanes	15	24	
																			S(o)	15	43	n/a	n/a	veh.				
12	1	10	12	1999	n/a	4 / N.MCGREG	4	yes	yes	no	no	16	32	17	15	4	2	1+2+3	2+3+4	n/a	n/a	16	32	veh.,ambul.	n/a	n/a	n/a	very serious
																			2+3+4	16	32	16	34	veh., ambul.,pol.	from opposite dir.	16	32	
																			1+2+3+4	16	34	16	44	veh., ambul.,pol.	from opposite dir.	16	34	one more ambulance and fire truck
																												traffic used median green zone
																			2+3+4	16	44	16	49	veh.,ambul.,pol.				traffic used median green zone also
																			2+3+4	16	49	17	5	veh.,ambul.,pol.				traffic used lane 1 only
																			2+3+4	17	5			veh.,pol.				traffic used lane 1 only
13	1	10	12	1999	n/a	7 / SH-288	2	yes	yes	no	no	16	37	17	5	1	5	1+S(m)	1+S(m)	n/a	n/a	16	41	veh.,pol.	n/a	n/a	n/a	looks like exit ramp
																			1+S)(m)	16	41	16	42	veh.,pol.,tech.,fire	main lane,	16	41	
																								truck, 2 ambul.	frontage road	16	42	
																			1+2+S(m)	16	42	16	55	veh.,pol.,tech.,fire				traffic used green zone between exit and frontage
																								truck, 2 ambul.				
																			1+S(m)	16	55	17	5	veh.,pol.,tech.,ambul.				traffic on lane 2 only
14	2	10	13	1999	n/a	22 / ELDORADO	3	yes	yes	no	c	5	37	6	17	1	2	1	1+S(m)	n/a	n/a	5	39	veh.				rear-end
																			S(m)	5	39	5	44	veh.				
																			S(m)+S(o)	5	44	5	45	veh., tech.	main lane	5	44	
																			S(m)+S(op.dir.m.)	5	45	5	46	veh., fire	oppos.dir.	5	45	
																			S(m)+S(op.dir.m.)	5	46	5	48	veh.,fire, ambul.	main lane	5	46	
																			S(m)	5	48	5	50	veh.,ambul.				
																			S(m)	5	50	5	58	veh.,ambul.,police.	main lane	5	50	at 6:17 one veh. moved out.
																			S(m)	5	58	6	3	veh.,police				second ready for moved out.
																			S(m)	6	3	6	17	veh.pol.,tech.	main lane	6	3	practically no more accident influence.
15	2	10	13	1999	5000 SW	6 / S.RICE	7	yes	yes	c	c	7	36	7	46	n/a	2	n/a	S(o)	n/a	n/a	7	41	veh.,tech.				first veh. moved out.
																			S(o)	7	41	n/a	n/a	veh.,tech.				at 7:46 one veh. and tech. on the shoulder
																												no influence on traffic.
16	2	10	13	1999	W.Loop	1 / E.ECHNUT	4	yes	yes	c	c	7	40	8	26	n/a	2	n/a	S(m)	n/a	n/a	7	41	veh., tech.				
																			S(m)+S(op.dir.m)	7	41	7	59	veh.,tech.	opposite dir.	7	41	Trastar tex. arrived.
																			S(m)	7	59	8	4	veh.,tech.				Trastar tex. go out
17	2	10	13	1999	n/a	12 Memorial	4	yes	yes	c	no	7	49	8	11	4	3	4	4	n/a	n/a	7	54	veh.				accident happened a few minutes ago.
																			3+4	7	54	7	56	veh., ambul.	main lane	7	54	traffic used exit ramp to pass the accident
																			4	7	56	8	0	veh.,tech.	main lane	7	56	
																			4+exit ramp	8	0	8	10	veh, tech, police	main lane	8	0	at 8:11 all veh. out of the roadway
																			S(o)	8	10			veh, tech, police				8:11 can be accident ending time.
18	2	10	13	1999	3900 SW	3 / WESTLAYAN	1	yes	yes	c	c	17	28	17	50	HOV	1	1+S(m)	1+S(m)	n/a	n/a	n/a	n/a	veh.				tech. problem with the bus on HOV lane
																			1+S(m)	17	46	17	49	veh.,police	HOV	n/a	n/a	at 17:47 recording continue and
																			1+S(m)	17	49	n/a	n/a	veh.,police., tech.	HOV	7	49	police was observed
19	2	10	13	1999	n/a	7 Pinemont	3	yes	no	c	c	16	43	17	20	1	2	1	1	n/a	n/a	16	49	veh.				
																			1	16	49	16	54	veh.,tech.,pol.	main lane	16	49	
																			1+2	16	54	17	8	veh.,tech.,pol.,ambul.	main lane	16	54	
																			1+2+3	17	8	17	12					all traffic blocked by police
																			1+2	17	12	17	17					
																			2+3	17	17	17	19					all vehicles moved out of the roadway.

Accident Descriptions: Houston, cont.

Accident #	Tape #	Date month	Date day	Date year	Highway	Camera I.D.	Total # of lanes one dir.	Shoulders outside	Shoulders median	Protective bariiers outside	Protective bariiers median	Start time of recording hr.	Start time of recording min.	Ending time of recording hr.	Ending time of recording min.	Lane where accident happened	# of vehicles involved in accident	Blocked lanes when accident happened	Blocked lanes and time of blockage during the accident: Lane	from hr.	from min.	to hr.	to min.	reason	Emergency arriving: Way	Time hr.	Time min.	Notice
20	2	10	13	1999	I 10	5 / WIRT	3	no	no	c	c	18	27	18	56	1	3	1	1	n/a	n/a	18	30	veh.				accident on frontage road
																			1	18	30	18	31	veh., fire.	frontage road	18	30	
																			1	18	31	18	35	veh.,fire,tech.	frontage road	18	31	
																			1	18	35	18	36	veh.,fire,tech.,ambul.	frontage road	18	35	
																			1	18	36	18	37	veh.,tech.,ambul.				
																			1	18	37	18	44	veh.,tech.,ambul.	frontage road	18	37	two more tech. arrived
																			1	18	44	18	46	veh.,tech.				
																			1	18	46	n/a	n/a	veh.,tech.	frontage road	18	46	one more tech. arrived
21	2	10	13	1999	W.Dallas	28	3	yes	yes	no	no	17	32	17	44	1	3	S(m)	S(m)	n/a	n/a	17	34	veh.,tech.				
																			S(m)+3	17	34	17	42	veh., tech.,pol.	main lane	17	34	
																			1+2+3	17	42	17	43	veh.,tech.,pol.,ambul.	main lane	17	42	all traffic blocked by police
																			S(m)+3	17	43	n/a	n/a	veh.,tech.,pol.,ambul.				
22	3	10	14	1999	I 45 North	16 / GULFBANK	4	yes	yes	x	n/a	6	20	6	32	1	2	1+S(m)	1+S(m)	6	20	6	23	veh.,tech.,pol.,ambul.,fire				
																			S(m)	6	24	6	29	veh.,tech.,pol.				
																			S(m)+1+2	6	29	6	30	veh.,tech.,pol.				
																			S(m)+1	6	30	6	32	veh.,tech.,pol.				
23	3	10	14	1999	GULF FWY	9 / BROADWAY	4	yes	no	c	c	6	31	6	43	1	1	1	1	6	31	6	36	veh.				technical problem
																			1	6	36	6	39	veh., tech.	main lane	6	34	
																			1+2	6	39	6	43	veh.,tech.,pol.	main lane	6	39	
24	3	10	14	1999	n/a	1/ ALABAMA	4	yes	yes	no	c	7	50	8	6	1	2	1+S(m)	1+S(m)	7	50	8	1	veh.,tech.,pol.				
																			1+S(m)	8	1	8	5	veh.,tech.,pol.,ambul.	main lane	8	1	
																			all	8	5	8	6					all lanes blocked by police
25	3	10	14	1999	South	17 BELTWAY	4	yes	yes	c	n/a	14	12	15	23	1	1	S(m)	S(m)	n/a	n/a	n/a	n/a	veh.				
																			1+S(m)	n/a	n/a	14	12	veh.,pol.,tech.				
																			1+S(m)	14	12	15	18	veh.,pol.,tech.				
																			all	15	18	15	22					traffic blocked by police
26	3	10	14	1999	I 45 North	14 / W L YORK	4	yes	yes	no	c	15	27	15	37	4	2	S(o)	S(o)	n/a	n/a	15	27	veh.				
																			S(o)	15	27	15	29	veh.				
																			S(o)	15	29	15	32	veh.,pol.	main lane	15	29	
																			S(o)	15	32	15	34	veh.,pol., tech.	main lane	15	32	
																			all	15	34	15	36					all lanes blocked by police
																			S(o)	15	36	15	37	tech., pol.				
27	3	10	14	1999	n/a	n/a	4	yes	no	c	c	16	45	16	51	2	2	2	2	n/a	n/a	16	50	veh.				accident happened a few minutes before recording
																			2	16	50	16	51	veh., tech.	main lane	16	50	veh. moved out by themselves
28	3	10	14	1999	n/a	14 Westheimer	4	yes	yes	n/a	c	16	32	16	55	1	3	1+S(m)	1+S(m)	n/a	n/a	18	36	veh., tech.				
																			1+S(m)	18	36	18	41	veh., tech	main lane	18	36	
																			1+S(m)	18	41	18	55	veh.,tech.,pol.	main lane	18	41	
																			S(m)	18	55			veh.,tech.,pol.				
29	3	10	15	1999	I 10 Katy	19 / TCJESTER	5	yes	yes	no	c	7	54	8	15	5	2	S(o)	S(o)	n/a	n/a	7	55	veh., tech.				
																			S(o)	7	55	8	8	veh.,tech.,pol.	main lane	7	55	
																			S(o)	8	8			veh.,tech.,pol.	main lane	8	8	
30	3	10	15	1999	5000 SW	6 / S. RICE	7	yes	yes	c	c	8	0	8	13	5	2	5	5	n/a	n/a	8	1	veh.				
																			5	8	1	8	11	veh.,tech.	main lane	8	1	
																			5	8	11	8	13	veh.,tech.,pol.	median shoulder	8	11	veh. moved out to the outside shoulder.

APPENDIX B

Accident Photos and Descriptions

San Antonio

ABBREVIATIONS USED FOR ACCIDENT DESCRIPTION

n/a – not applicable

c – concrete

HOV – high occupancy vehicles lane

S(o), Shl. Out. – outside shoulder

S(m), Shl. Med. – median shoulder

S (op.m.) – median shoulder on opposite direction

Lane 1, etc. – traffic lane number from the median

R (ext.), R(ent.) – exit or entrance ramp

veh. – vehicle(s) involved in the accident

pol. – police vehicles

amb. – ambulance vehicle

fire – fire truck

tow. – towing vehicle

reg.dir.main lanes – regular direction main traffic lanes

shl. – shoulder

opp.dir. main lanes – opposite direction main traffic lanes

San Antonio. Accident # 1.

Accident #	1
Tape #	4
Day	5/3/99
Camera I.D.	IH 10E Vance Jackson
Time when recording start:	8:01
Time when recording finished:	8:57
Number of traffic lanes in one direction:	3
Shoulders:	outside + median
Protective barriers:	Median (metal)
Number of vehicles involved in accident:	1
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time From	Time To	Duration, min.	Reason for blockage	
Shl. (Med.)	8:01	8:14	13	vehicle	minor
Shl. (Med.) + 1	8:14	8:15	1	vehicles	medium
Shl. (Med.)	8:15	8:53	38	veh., pol., tow	minor
Shl. (Med.) + 1	8:53	8:57	4	veh., pol., tow	medium

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police	8:31	reg. Dir. Main lanes	8:57
tow truck	8:49	reg. Dir. Main lanes	8:57

San Antonio. Accident # 2.

Accident #	2
Tape #	4
Day	5/10/99
Camera I.D.	US 281N at the River
Time when recording start:	7:17
Time when recording finished:	8:22
Number of traffic lanes in one direction:	5
Shoulders:	outside + median
Protective barriers:	Median (concrete)+ Outside (metal)
Number of vehicles involved in accident:	1
Traffic lane where accidents happened:	2

Blockage					Influence on traffic
Lane (s)	Time From	Time To	Duration, min.	Reason for blockage	
1,2,3,4	7:17	8:00	43	tanker truck, pol.	major
1,2,3,4,5	8:00	8:01	1	tanker truck, pol., tow	stop
1,2,3,4	8:01	8:05	4	tanker truck, pol., tow	major
1,2,3	8:05	8:22	17	tanker truck, pol., tow	major
no	8:22				no

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
ambulance	7:21	reg. Dir. Main lanes	7:37
police 1	7:23	reg. Dir. Opp. lanes + shl.	8:21
tow truck	7:59	reg. Dir. Main lanes	8:21
police 2	8:11	reg. Dir. Main lanes	8:21

San Antonio. Accident # 3.

Accident #	3
Tape #	4
Day	5/12/99
Camera I.D.	IH 35S at St. Mary's
Time when recording start:	15:40
Time when recording finished:	15:47
Number of traffic lanes in one direction:	3 + 2 Exit only lanes
Shoulders:	outside
Protective barriers:	Median (concrete)+ Outside (concrete)
Number of vehicles involved in accident:	2
Traffic lane where accidents happened:	3

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
3 no	15:40 15:46	15:46	6	vehicles	major no

San Antonio. Accident # 4.

Accident #	4
Tape #	4
Day	5/13/99
Camera I.D.	IH 10E at IH 410
Time when recording start:	15:20
Time when recording finished:	15:32
Number of traffic lanes in one direction:	3+ Ramp (exit)
Shoulders:	outside (Exit Ramp)
Protective barriers:	Median (metal)+ Outside (metal)
Number of vehicles involved in accident:	2
Traffic lane where accidents happened:	Ramp (exit)

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Shl.out.	15:20	15:31	11	veh.	minor
Shl.out.	15:31	15:32	1	veh.,pol.	minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police	15:31	reg. Dir. Main lanes	15:32

San Antonio. Accident # 5.

Accident #	5
Tape #	4
Day	6/3/99
Camera I.D.	IH 410E Fredericksburg
Time when recording start:	16:01
Time when recording finished:	16:57
Number of traffic lanes in one direction:	3 + exit ramp
Shoulders:	median + outside
Protective barriers:	Median (metal)+ Outside (metal)
Number of vehicles involved in accident:	2
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Med. Shl. + 1	16:01	16:36	35	veh., pol., amb.	major
Med. Shl. + 1	16:36	16:57	21	veh., pol., tow.	medium
no	16:57				no

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police	16:01	reg. Dir. Main lanes	16:57
tow truck	16:12	reg. Dir. Main lanes	16:56
ambulance	16:15	reg. Dir. Main lanes	16:22

San Antonio. Accident # 6.

Accident #	6
Tape #	4
Day	6/8/99
Camera I.D.	IH 10W at IH 35
Time when recording start:	18:06
Time when recording finished:	18:52
Number of traffic lanes in one direction:	4 + Ramp (entrance/exit)
Shoulders:	median + outside
Protective barriers:	Median (concretel)+ Outside (metal/concrete)
Number of vehicles involved in accident:	3
Traffic lane where accident happened:	3

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
3	18:06	18:11	5	veh.	major
3	18:06	18:13	2	veh., pol.	major
3,4, ramp (ent.)	18:13	18:14	1	veh., pol.	stop
outside shl. (end of ent. Ramp gore)	18:14	18:21	7	veh., pol.,	major
outside shl. (end of ent. Ramp gore)	18:21	18:31	10	veh., pol., tow	minor
outside shl. (end of ent. Ramp gore) + 4	18:31	18:43	12	veh., pol., tow	medium
outside shl. (end of ent. Ramp gore) + 3,4	18:43	18:47	4	vej/. Pol., tow	major
outside shl. (end of ent. Ramp gore) + 4	18:47	18:52	5	veh., pol., tow	medium
no	18:52				no

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police 1	18:11	reg. Dir. Main lanes	18:52
police 2	18:14	reg. Dir. Main lanes	18:52
tow truck	18:30	reg. Dir. Main lanes	18:51

San Antonio. Accident # 7.

Accident #	7
Tape #	4
Day	6/11/99
Camera I.D.	IH 10E IH 410
Time when recording start:	14:08
Time when recording finished:	14:39
Number of traffic lanes in one direction:	2 + Ramp (exit)+ Ramp (entrance)
Shoulders:	none
Protective barriers:	median (metal) + outside (metal)
Number of vehicles involved in accident:	4
Traffic lane where accident happened:	Ramp (exit)

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Ramp (ex) no	14:08 14:39	14:39	31	veh., pol., tow	major no

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
tow truck	14:21	reg. Dir. Main lanes	14:39
police 1	14:35	reg. Dir. Main lanes	14:39
police 2	14:38	reg. Dir. Main lanes	14:39

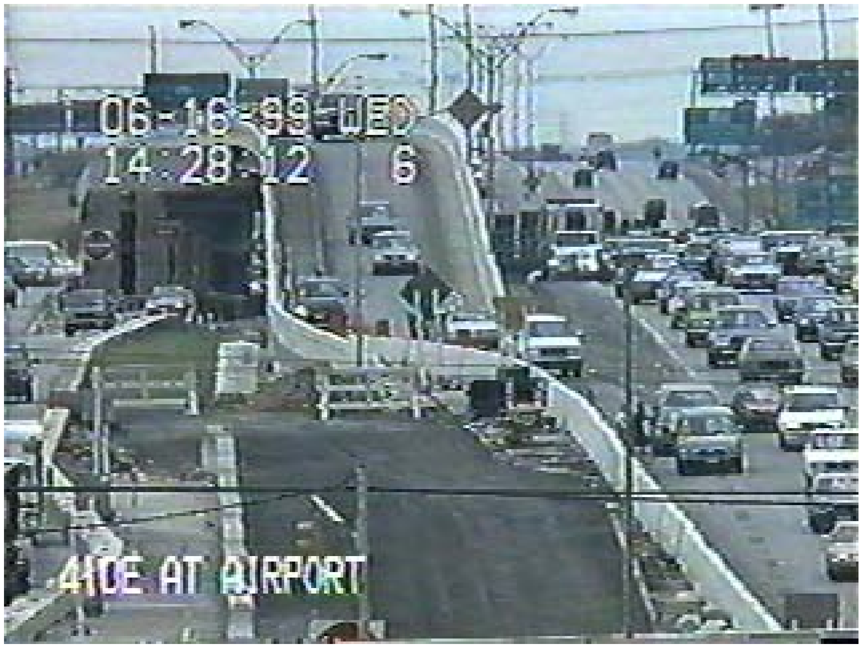
San Antonio. Accident # 8.

Accident #	8
Tape #	4
Day	6/15/99
Camera I.D.	I H10W at Probandt
Time when recording start:	8:51
Time when recording finished:	9:27
Number of traffic lanes in one direction:	4 + ramp (exit)
Shoulders:	median + outside
Protective barriers:	median (metal) + outside (metal)
Number of vehicles involved in accident:	3
Traffic lane where accident happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Med. Shl.	8:51	8:53	2	veh.	minor
Med. Shl. + 1	8:53	9:27	34	veh., pol., amb., tow	minor
no	9:27				no

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police 1	8:53	reg. Dir. Main lanes	9:27
ambulance	8:53	reg. Dir. Main lanes	9:17
police 2	9:02	reg. Dir. Main lanes	9:27
tow truck 1	9:02	reg. Dir. Main lanes	9:23
tow truck 2	9:12	reg. Dir. Main lanes	9:26

San Antonio. Accident # 9.



Accident #	9
Tape #	5
Day	6/16/99
Camera I.D.	I410E at Airport
Time when recording start:	14:25
Time when recording finished:	14:43
Number of traffic lanes in one direction:	3 + ramp (entrance)
Shoulders:	median + outside
Protective barriers:	median (metal) + outside (concrete)
Number of vehicles involved in accident:	3
Traffic lane where accident happened:	ramp (entrance)

Blockage					Influence on traffic
Lane (s)	Time From	Time To	Duration, min.	Reason for blockage	
end of ramp gore	14:25	14:28	3	veh.	medium
end of ramp gore	14:28	14:43	15	veh., pol., tow	medium
no	14:43				no

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police	14:28	ramp (entrance)	14:43
tow truck	14:32	reg. Dir. Main lanes	14:43

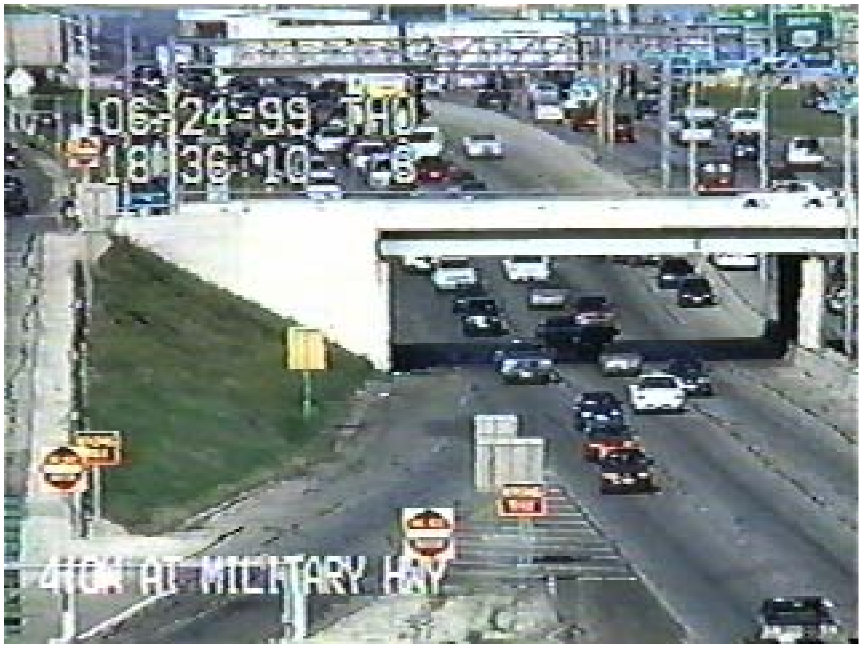
San Antonio. Accident # 10.

Accident #	10
Tape #	5
Day	6/23/99
Camera I.D.	I35N at Powell
Time when recording start:	8:09
Time when recording finished:	8:32
Number of traffic lanes in one direction:	5 + exit ramp
Shoulders:	outside
Protective barriers:	median (concrete) + outside (concrete)
Number of vehicles involved in accident:	2
Traffic lane where accident happened:	4

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
4	8:09	8:13	4	veh., pol.	medium
4,5	8:13	8:15	2	veh., pol.	major
outside shl. + 5	8:15	8:32	17	veh., pol., tow	medium

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police 1	8:09	reg. Dir. Main lanes	8:10
police 2	8:09	reg. Dir. Main lanes	8:31
police 3	8:13	reg. Dir. Main lanes	8:31
police 4	8:14	reg. Dir. Main lanes	8:21
tow truck	8:18	reg. Dir. Main lanes	8:30

San Antonio. Accident # 11.



Accident #	11
Tape #	5
Day	6/24/99
Camera I.D.	I410W at Military Hwy.
Time when recording start:	18:20
Time when recording finished:	19:01
Number of traffic lanes in one direction:	3 + ramp (exit)
Shoulders:	median + outside
Protective barriers:	median (concrete)
Number of vehicles involved in accident:	3
Traffic lane where accident happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
med. Shl.	18:20	18:30	10	veh.	major
med. Shl. + 1	18:30	19:01	31	veh., pol., tow	major
no	19:01				no

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police 1	18:30	opp. Dir. Main lanes	19:00
police 2	18:32	reg. Dir. Main lanes + shl.	19:01
tow truck 1	18:46	reg. Dir. Main lanes	18:58
tow truck2	18:46	reg. Dir. Main lanes	19:00

San Antonio. Accident # 12.

Accident #	12
Tape #	5
Day	6/25/99
Camera I.D.	IH10E IH 410
Time when recording start:	10:51
Time when recording finished:	11:33
Number of traffic lanes in one direction:	3 + ramp (entrance)
Shoulders:	outside
Protective barriers:	outside (metal)
Number of vehicles involved in accident:	4
Traffic lane where accident happened:	1

Blockage					Influence on traffic
Lane (s)	Time From	Time To	Duration, min.	Reason for blockage	
Med. Shl.	10:51	11:01	10	veh.	
Med. Shl.	11:01	11:33	32	veh., pol., amb., tow	minor
no	11:33				no

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police 1	11:01	ramp (entrance)	11:30
ambulance	11:05	reg. Dir. Main lanes	11:14
tow truck	11:08	opp. Dir. Med. Shl.	11:21
police 2	11:17	reg. Dir. Main lanes	11:33

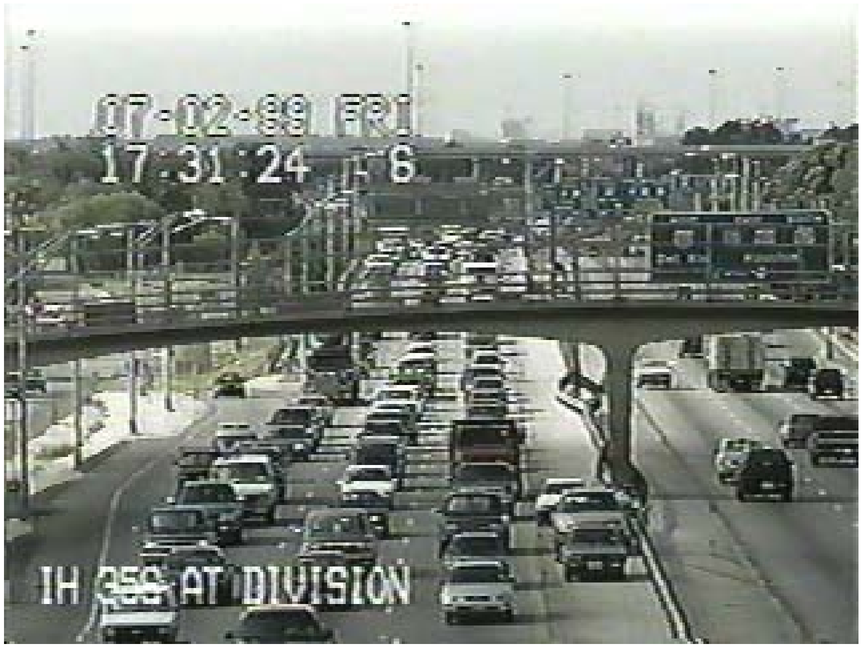
San Antonio. Accident # 13.

Accident #	13
Tape #	5
Day	7/1/99
Camera I.D.	281 N at Alamo Stadium
Time when recording start:	15:45
Time when recording finished:	15:59
Number of traffic lanes in one direction:	3
Shoulders:	median + outside
Protective barriers:	median (concrete) + outside (concrete)
Number of vehicles involved in accident:	2
Traffic lane where accident happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
1	15:45	15:58	13	veh.,pol.	minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police 1	15:45	reg. Dir. Main lanes	15:58
police 2	15:46	reg. Dir. Main lanes	15:58
tow truck	15:54	reg. Dir. Main lanes	15:57

San Antonio. Accident # 14.



Accident #	14
Tape #	5
Day	7/2/99
Camera I.D.	IH 35S at Division
Time when recording start:	17:29
Time when recording finished:	17:41
Number of traffic lanes in one direction:	3 + ramp (entrance)
Shoulders:	median
Protective barriers:	median (metal)
Number of vehicles involved in accident:	3
Traffic lane where accident happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
med. Shl.	17:29	17:33	4	veh.	minor
med. Shl.	17:33	17:41	8	veh., pol., tow	minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police 1	17:33	ramp (entrance)	17:41
tow truck	17:38	reg. Dir. Main lanes	17:41

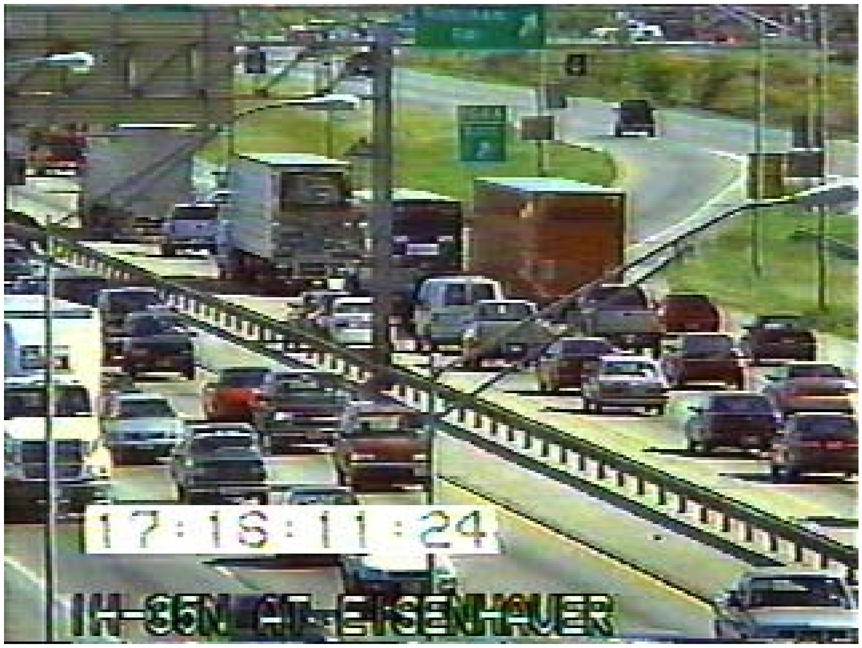
San Antonio. Accident # 15.

Accident #	15
Tape #	6
Day	5/23/00
Camera I.D.	IH 35N at Eisenhaver
Time when accident reported:	11:43
Time when recording start:	12:00
Time when recording finished:	12:43
Number of traffic lanes in one direction:	3 + entrance ramp
Shoulders:	outside and meddian
Protective barriers:	median (metal)
Number of vehicles involved to accident:	2
Traffic lane where accidents happened:	entrance ramp (upnstream of ramp gore)

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
out of road	11:43	12:01	18	veh.	no
out of road	12:01	12:43	42	veh., pol.	no

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police	12:01	frontage road	12:43
tow truck	12:27	regular direction main lanes	12:41

San Antonio. Accident # 16.



Accident #	16
Tape #	6
Day	5/23/00
Camera I.D.	IH 35N at Eisenhaver
Time when recording start:	17:15
Time when recording finished:	17:42
Number of traffic lanes in one direction:	3 + exit ramp
Shoulders:	outside and median
Protective barriers:	median (metal)
Number of vehicles involved to accident:	2
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
S(m)	17:15	17:40	25	vehicles	minor
S(m)	17:40	17:42	2	veh.,pol.	minor
all	17:42	17:43	1	pol.	stop
no	17:43				no

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police	17:40	regular direction main lanes	17:43

San Antonio. Accident # 17.

Accident #	17
Tape #	6
Day	5/23/00
Camera I.D.	LP 410 N at Ingram Rd.
Time when recording start:	7:56
Time when recording finished:	8:18
Number of traffic lanes in one direction:	3
Shoulders:	outside + median
Protective barriers:	median (concrete)
Number of vehicles involved to accident:	2
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time From	Time To	Duration, min.	Reason for blockage	
S(m)	7:56	8:00	4	veh.	minor
S(m)	8:00	8:12	12	veh., pol.	minor
S(m)	8:12	8:16	4	veh., pol.	minor
no	8:16				no

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police	8:00	regular direction main lanes	8:16

San Antonio. Accident # 18.

Accident #	18
Tape #	6
Day	5/23/00
Camera I.D.	LP 410 W at Military
Time when recording start:	13:06
Time when recording finished:	14:01
Number of traffic lanes in one direction:	3 + exit ramp
Shoulders:	outside and median
Protective barriers:	median (concrete)
Number of vehicles involved to accident:	2
Traffic lane where accidents happened:	2

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
2	13:06	13:10	4	veh.	major
2	13:10	13:14	4	veh.,amb.	major
2	13:14	13:16	2	veh.,amb.,pol.	major
2	13:16	13:18	2	veh.,amb.,pol.	major
2+3	13:18	13:19	1	veh.,amb.,pol.,fire	major
1+2+S(o)	13:19	13:21	2	veh.,amb.,pol.,fire	major
1+2+S(o)+S(op.m.)	13:21	13:23	2	veh.,amb.,pol.,fire	major
2+3+S(o)	13:24	13:30	6	veh.,amb.,pol.,fire	major
2+3+S(o)	13:30	13:35	5	veh.,amb.,pol.,fire	major
1+2+3+S(o)	13:35	13:50	15	veh.,amb.,pol.,fire,tow.	major
3+S(o)	13:50	13:51	1	veh.,amb.,pol.,fire,tow.	major
3+S(o)	13:51	14:01	10	police	major

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
ambulance-1	13:10	reg. dir. main lanes	13:38
police-1	13:14	reg. dir. main lanes	13:54
police-2	13:16	reg. dir. main lanes	14:01
fire truck-1	13:18	reg. dir. main lanes+shl.	13:51
police-3	13:19	reg. dir. main lanes	14:01
ambulance-2	13:19	reg. dir. main lanes+sh.	13:47
fire truck-2	13:21	opp. dir. main lanes	13:23
ambulance-3	13:30	reg.dir. main lanes	13:46
tow truck-1	13:34	reg.dir. main lanes	13:48
tow truck-2	13:34	reg.dir. main lanes	13:55
fire truck-3	13:36	reg.dir. main lanes	13:42
tow truck-3	13:36	reg.dir. main lanes	14:01

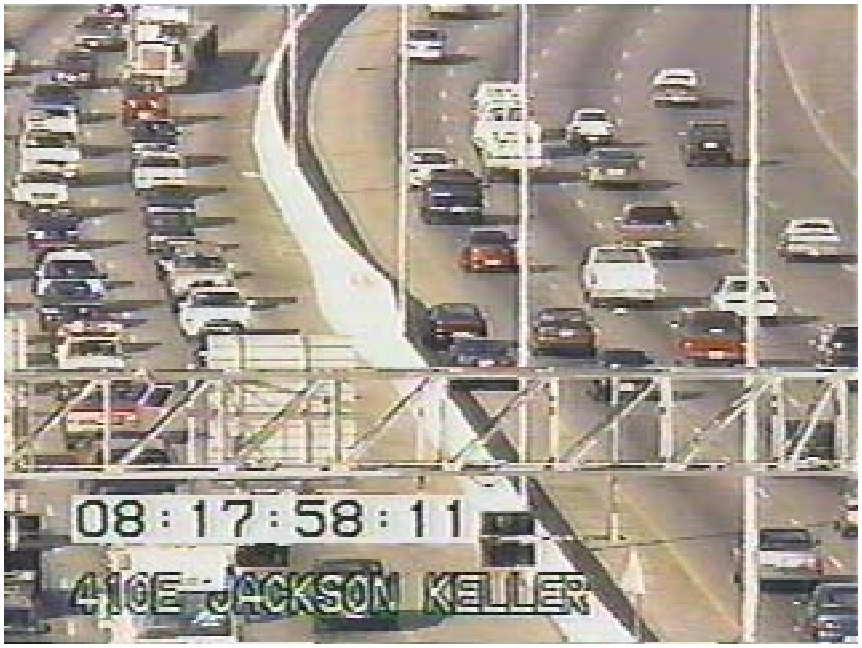
San Antonio. Accident # 19.

Accident #	19
Tape #	6
Day	5/23/00
Camera I.D.	LP 410 E Fredericksburg
Time when accident reported:	16:48
Time when recording start:	16:52
Time when recording finished:	18:18
Number of traffic lanes in one direction:	3
Shoulders:	outside and median
Protective barriers:	median (concrete)
Number of vehicles involved to accident:	2
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
S(m)	16:52	17:11	19	vehicles	minor
S(m) +1	17:11	17:23	12	veh., amb.	major
S(m) +1	17:24	17:48	24	veh., tow	major
S(m)	17:48	18:00	12	veh., pol.	medium
S(m)	18:00	18:05	5	veh., pol., tow	minor
S(m)	18:05	18:11	6	veh., pol., tow	medium
S(m)	18:11	18:17	6	veh., pol.,tow, fire	major

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
ambulance	17:11	Reg. Dir. Main lanes	17:23
tow truck - 1	17:24	Reg. Dir. Main lanes	17:48
police	17:48	Reg. Dir. Main lanes + Shl.	18:17
tow truck - 2	18:00	Reg. Dir. Main lanes	18:14
tow truck - 3	18:05	Reg. Dir. Main lanes	18:17
fire truck	18:11	Reg. Dir. Main lanes + Shl.	18:17

San Antonio. Accident # 20.

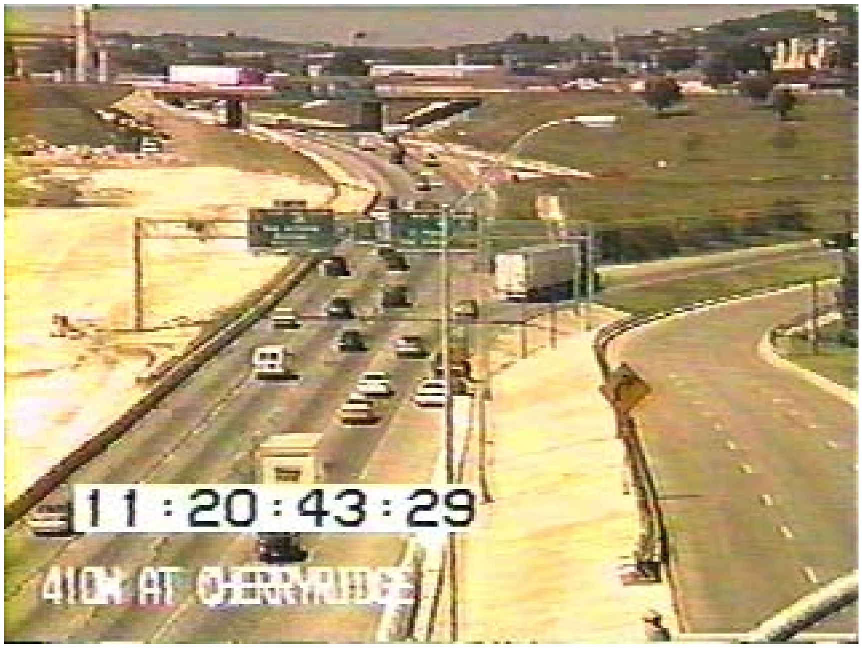


Accident #	20
Tape #	6
Day	5/23/00
Camera I.D.	LP 410 E Jackson Keller
Time when accident reported:	8:09
Time when recording start:	8:15
Time when recording finished:	8:49
Number of traffic lanes in one direction:	4 + entrance ramp
Shoulders:	outside and median
Protective barriers:	median (concrete)
Number of vehicles involved to accident:	2
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
S(m)	8:15	8:21	6	vehicles	minor
S(m)	8:21	8:32	11	veh., pol.	minor
S(m)	8:32	8:46	14	veh., pol., amb	minor
S(m)	8:46	8:49	3	veh., pol.	minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police	8:21	Reg. Dir. main lanes	8:49
ambulance	8:32	Reg. Dir. main lanes	8:46

San Antonio. Accident # 21.

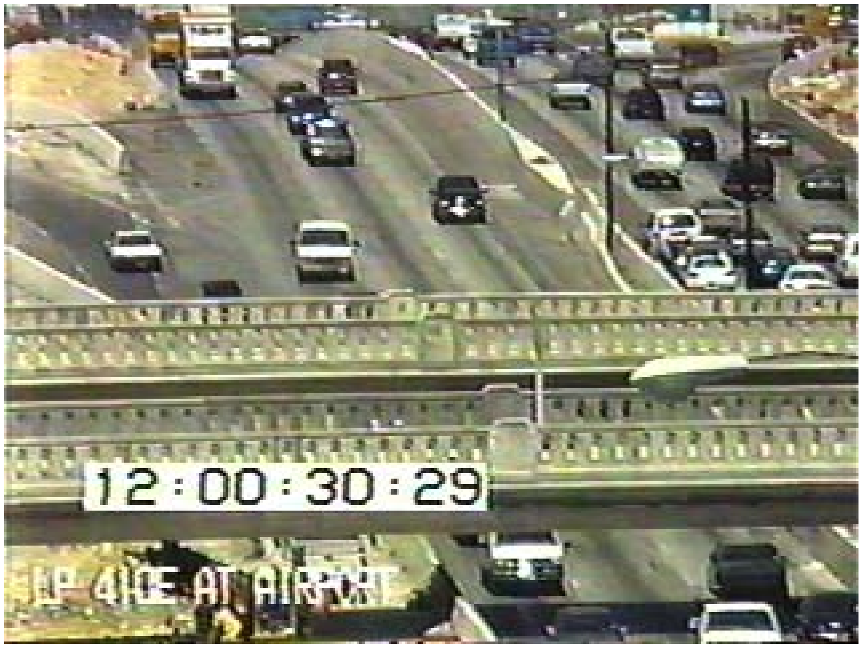


Accident #	21
Tape #	6
Day	5/23/00
Camera I.D.	LP 410 W at Cherryridge
Time when accident reported:	11:01
Time when recording start:	11:12
Time when recording finished:	11:23
Number of traffic lanes in one direction:	3 + exit ramp
Shoulders:	outside
Protective barriers:	median (concrete)
Number of vehicles involved to accident:	2
Traffic lane where accidents happened:	exit ramp

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
S(o)	11:01	11:12	11	veh.	minor
S(o)	11:12	11:22	10	veh., pol.	minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police	11:12	Reg. Dir. main lanes	11:22

San Antonio. Accident # 22.



Accident #	22
Tape #	7
Day	5/24/00
Camera I.D.	LP 410E at Airport
Time when recording start:	12:00
Time when recording finished:	12:09
Number of traffic lanes in one direction:	3+ramp (exit)
Shoulders:	median
Protective barriers:	median (concrete)
Number of vehicles involved in accident:	2
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
med. Shl. no	12:00 12:07	12:07	7	veh., pol. no	minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police 1 police 2	12:00 12:05	reg. Dir. Main lanes reg. Dir. Main lanes	12:03 12:07

San Antonio. Accident # 23.

Accident #	23
Tape #	7
Day	5/24/00
Camera I.D.	I 410W at Harry Wurzbach
Time when recording start:	14:52
Time when recording finished:	15:46
Number of traffic lanes in one direction:	3+ramp (exit)
Shoulders:	median + outside
Protective barriers:	median (concrete) + outside (metal)
Number of vehicles involved in accident:	5
Traffic lane where accidents happened:	3

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
3 + out. Shl.	14:52	14:55	3	vehicles	major
out. Shl	14:55	15:03	8	veh., fire truck	medium
3 + out. Shl	15:03	15:06	3	veh., fire truck	medium
out. Shl.	15:06	15:12	6	veh., fire, pol.	medium
3 + out. Shl.	15:12	15:24	12	veh., fire, pol.,amb.,tow.	major
out. Shl.	15:24	15:45	21	veh., pol.,tow.	minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
fire truck	15:00	reg. Dir. Main lanes	15:24
police 1	15:08	reg. Dir. Main lanes	15:45
polcie 2	15:08	reg. Dir. Main lanes	15:13
ambulance	15:12	reg. Dir. Main lanes	15:19
tow truck 1	15:23	reg. Dir. Main lanes	15:42
tow truck 2	15:43	reg. Dir. Main lanes	15:45

San Antonio. Accident # 24.

Accident #	24
Tape #	7
Day	5/24/00
Camera I.D.	LP 410E Fredericksburg
Time when recording start:	17:07
Time when recording finished:	17:45
Number of traffic lanes in one direction:	4+ramp (entrance)
Shoulders:	median + outside
Protective barriers:	median (concrete) + outside (metal)
Number of vehicles involved in accident:	1
Traffic lane where accidents happened:	4

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Ramp gore, shl. Out. Shl.	17:07 17:16	17:16 17:43	9 27	vehicle veh., police	medium minor

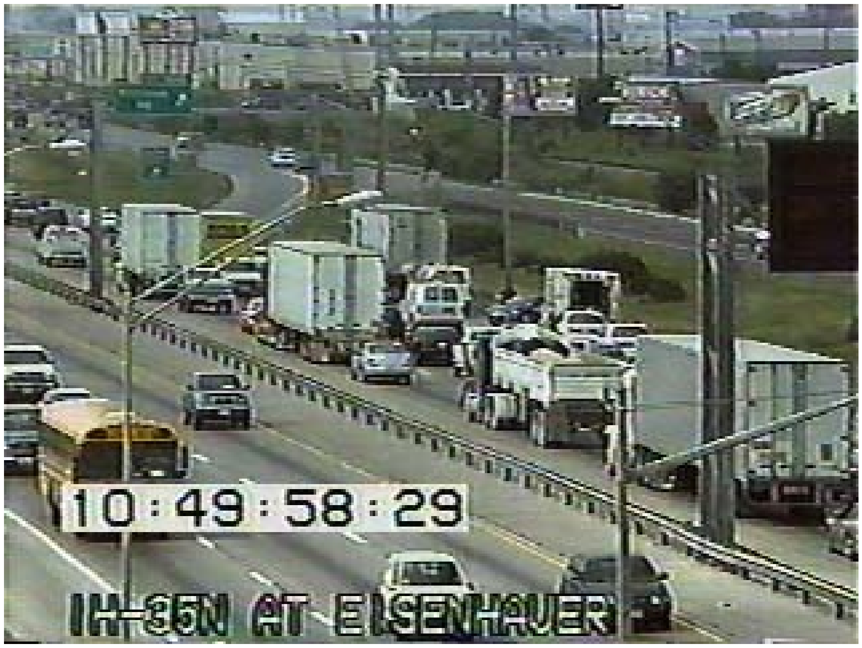
Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
police	17:16	reg. Dir. Main lanes	17:43

San Antonio. Accident # 25.

Accident #	25
Tape #	7
Day	5/24/00
Camera I.D.	LP 410W at Babcock
Time when recording start:	19:02
Time when recording finished:	19:22
Number of traffic lanes in one direction:	3+ramp (exit)
Shoulders:	median + outside
Protective barriers:	median (concrete)
Number of vehicles involved in accident:	1
Traffic lane where accidents happened:	3

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Shl. (out)	19:02	19:22	20	veh.	no

San Antonio. Accident # 26.

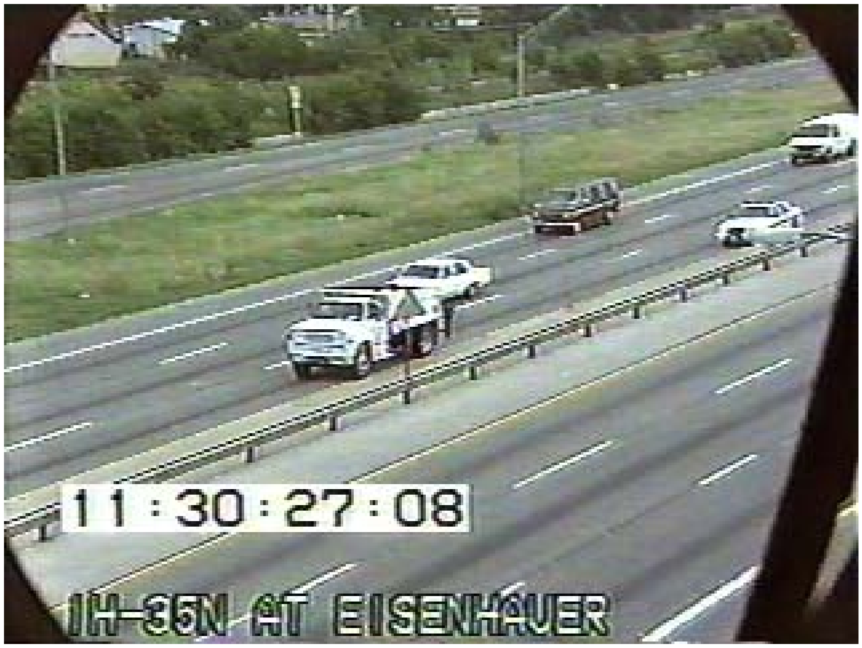


Accident #	26
Tape #	8
Day	5/25/00
Camera I.D.	IH35N at Eisenhauer
Time when accident reported:	10:34
Time when recording start:	10:49
Time when recording finished:	11:39
Number of traffic lanes in one direction:	3 + Ramp (Exit)
Shoulders:	outside + median
Protective barriers:	Median (metal)
Number of vehicles involved in accident:	2
Traffic lane where accidents happened:	3

Blockage					Influence on traffic
Lane (s)	Time From	Time To	Duration, min.	Reason for blockage	
Out. Shl.	10:34	10:49	15	Veh.	Medium
Out. Shl.	10:49	11:00	11	Veh. Pol. Amb.	Medium
Out. Shl.	11:00	11:18	18	Veh. Pol. Amb. Tow	Minor
Out. Shl.	11:18	11:39	21	Pol.	No

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Police 1	10:49	Reg. Dir. Main Lanes	11:18
Police 2	10:49	Reg. Dir. Main Lanes	11:39
Ambulance 1	10:49	Reg. Dir. Main Lanes	11:00
Ambulance 2	10:49	Reg. Dir. Main Lanes	11:14
Tow Truck	11:00	Reg. Dir. Main Lanes + Out. Shl.	11:18

San Antonio. Accident # 27.

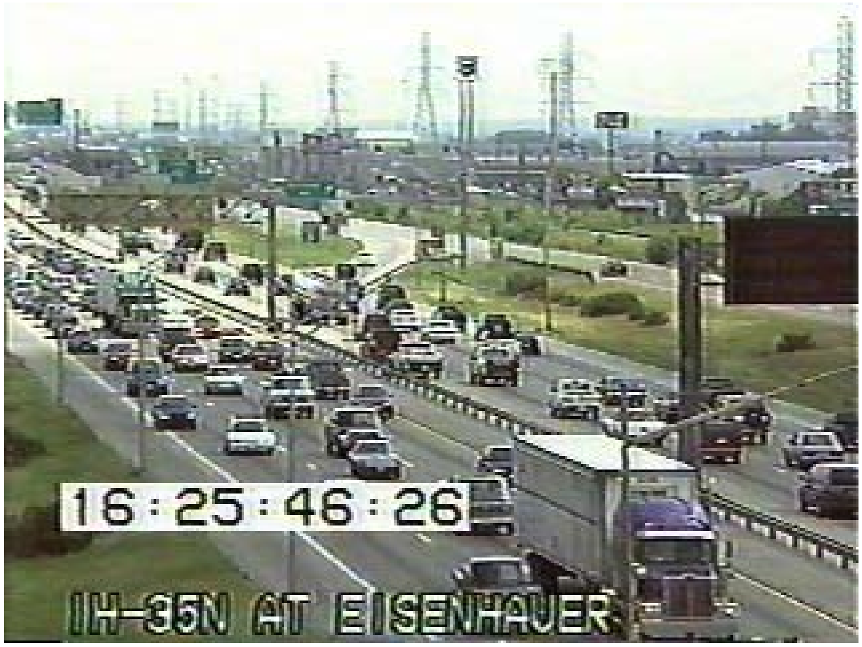


Accident #	27
Tape #	8
Day	5/25/00
Camera I.D.	IH35N at Eisenhauer
Time when recording start:	11:13
Time when recording finished:	11:39
Number of traffic lanes in one direction:	3 + Ramp (Exit)
Shoulders:	outside + median
Protective barriers:	Median (metal)
Number of vehicles involved in accident:	1
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
1	11:13	11:37	24	Veh. Pol.	Major
No	11:37				No

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Police	11:13	Reg. Dir. Main Lanes	11:38

San Antonio. Accident # 28.

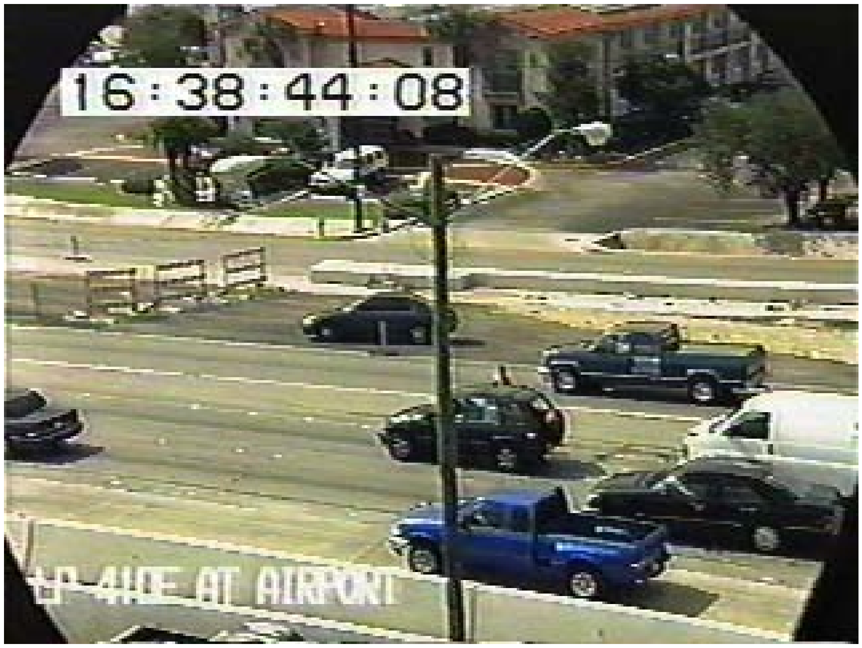


Accident #	28
Tape #	8
Day	5/25/00
Camera I.D.	IH35N at Eisenhauer
Time when accident reported:	16:22
Time when recording start:	16:24
Time when recording finished:	17:14
Number of traffic lanes in one direction:	3 + Ramp (Exit)
Shoulders:	outside + median
Protective barriers:	Median (metal)
Number of vehicles involved in accident:	2
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Med. Shl.	16:24	16:34	10	Veh.	Minor
Med. Shl.	16:34	16:37	3	Veh. Pol. Amb.	Medium
Med. Shl.	16:37	17:14	37	Veh. Pol. Tow	Minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Police	10:49	Reg. Dir. Main Lanes	17:14
Ambulance	16:34	Opp. Dir. Main Lanes	16:35
Tow	17:07	Reg. Dir. Main Lanes	17:14

San Antonio. Accident # 29.



Accident #	29
Tape #	8
Day	5/25/00
Camera I.D.	LP 410E at Airport
Time when accident reported:	16:33
Time when recording start:	16:37
Time when recording finished:	17:07
Number of traffic lanes in one direction:	3 + Ramp (Entrance)
Shoulders:	Median + Outside
Protective barriers:	Median (concrete)
Number of vehicles involved in accident:	3
Traffic lane where accidents happened:	3

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
3	16:33	16:37	4	Veh.	Major
3	16:37	16:44	7	Veh. Pol.	Major
3	16:44	17:07	23	Veh. Pol. Amb. Tow	Major

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
*Police 1	16:37	Reg. Dir. Main Lanes	17:07
Ambulance	16:43	Reg. Dir. Main Lanes	16:58
*Police 2	16:48	Reg. Dir. Main Lanes	17:07
Tow	16:52	Reg. Dir. Main Lanes	17:07

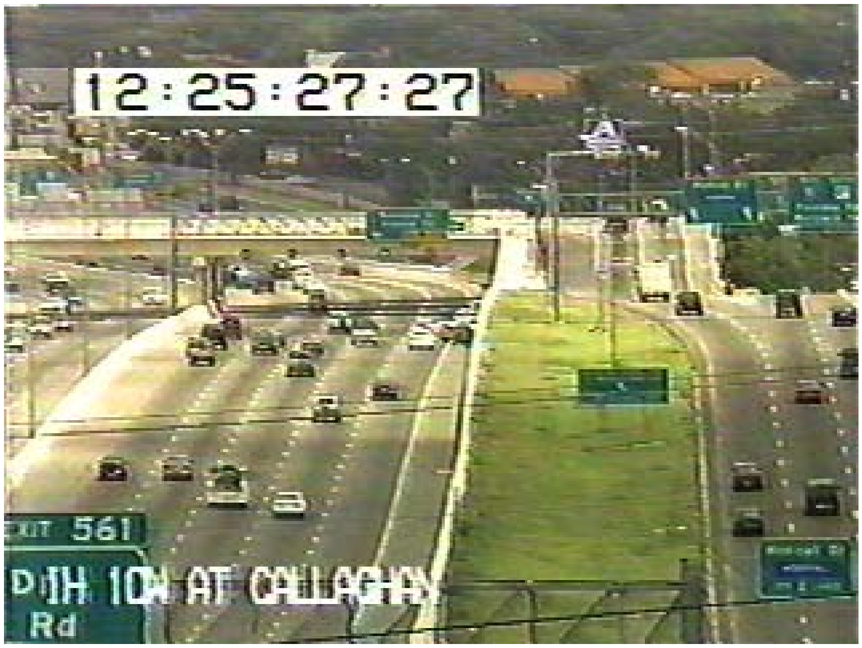
San Antonio. Accident # 30.

Accident #	30
Tape #	8
Day	5/25/00
Camera I.D.	LP410W at Cherryridge
Time when accident reported:	18:56
Time when recording start:	18:59
Time when recording finished:	19:36
Number of traffic lanes in one direction:	4 + Ramp (Entrance)
Shoulders:	Median + Outside
Protective barriers:	Med. (Concrete) + Out. (Metal)
Number of vehicles involved in accident:	3
Traffic lane where accidents happened:	Ramp (entrance)

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Out. Shl.	18:56	19:03	7	Veh.	Minor
Out. Shl.	19:03	19:36	33	Veh. Amb. Pol. Tow	Minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Ambulance	19:03	Reg. Dir. Main Lanes + Shl.	19:18
Police 1	19:08	Reg. Dir. Main Lanes	19:36
Police 2	19:11	Reg. Dir. Main Lanes	19:36
Tow	19:29	Reg. Dir. Main Lanes	19:35
Police 3	19:32	Reg. Dir. Main Lanes	19:36

San Antonio. Accident # 31.



Accident #	31
Tape #	8
Day	5/25/00
Camera I.D.	IH 10W at Callaghan
Time when accident reported:	12:18
Time when recording start:	12:23
Time when recording finished:	12:53
Number of traffic lanes in one direction:	5
Shoulders:	Median + Outside
Protective barriers:	Med. (Concrete) + Out. (Concrete)
Number of vehicles involved in accident:	4
Traffic lane where accidents happened:	5

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
5 + Out. Shl.	12:18	12:25	7	Veh.	Minor
5 + Out. Shl.	12:25	12:53	28	Veh. Pol. Amb. Tow	Minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Police 1	12:25	Reg. Dir. Main Lanes	12:53
Police 2	12:25	Reg. Dir. Main Lanes	12:53
Ambulance	12:27	Reg. Dir. Main Lanes	12:49
Tow	12:37	Reg. Dir. Main Lanes	12:53

San Antonio. Accident # 32.

Accident #	32
Tape #	8
Day	5/25/00
Camera I.D.	IH 10W at West Ave.
Time when accident reported:	16:09
Time when recording start:	16:11
Time when recording finished:	16:42
Number of traffic lanes in one direction:	3 + Ramp (Exit)
Shoulders:	Median + Outside
Protective barriers:	Med. (Concrete)
Number of vehicles involved in accident:	3
Traffic lane where accidents happened:	Ramp (Exit)

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Out. Shl. + Ramp (Exit)	16:09	16:13	4	Veh.	Minor
Out. Shl. + Ramp (Exit)	16:13	16:27	14	Veh. , Pol.	Minor
Out. Shl. + Ramp (Exit)	16:27	16:42	15	Veh. Pol. Tow	Minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Police	16:13	Reg. Dir. Main Lanes	16:42
Tow	16:27	Reg. Dir. Main Lanes	16:42

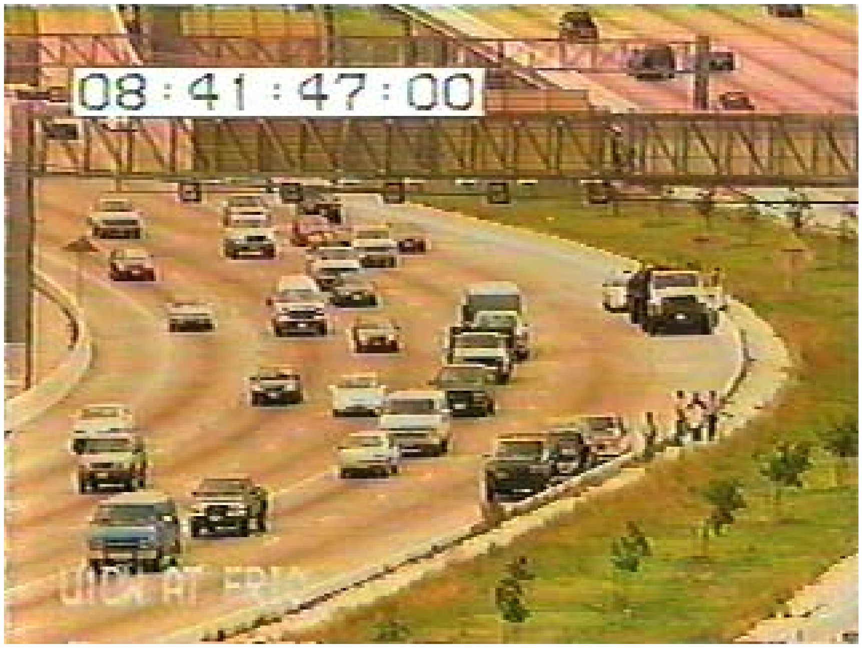
San Antonio. Accident # 33.

Accident #	33
Tape #	8
Day	5/25/00
Camera I.D.	LP 410W at Callaghan
Time when recording start:	7:13
Time when recording finished:	7:53
Number of traffic lanes in one direction:	3 + Ramp (Exit)
Shoulders:	Median
Protective barriers:	Med. (Concrete)
Number of vehicles involved in accident:	3
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
1,2, Med. Shl.	7;13	7;14	1	Vehicles	Major
1 + Med. Shl.	7:14	7:19	5	Veh.	Major
1 + Med. Shl.	7:19	7:53	34	Veh. Pol. Amb. Tow	Major

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Police 1	7:19	Reg. Dir. Main Lanes + Shl.	7:52
Police 2	7:20	Reg. Dir. Main Lanes + Shl.	7:52
Ambulance	7:22	Reg. Dir. Main Lanes	7:52
Police 3	7:30	Reg. Dir. Main Lanes + Shl.	7:52
Tow	7:42	Reg. Dir. Main Lanes	7:51

San Antonio. Accident # 34.



Accident #	34
Tape #	8
Day	5/25/00
Camera I.D.	IH10E at Y / IH10W at Frio
Time when accident reported:	8:04
Time when recording start:	8:40
Time when recording finished:	9:31
Number of traffic lanes in one direction:	5
Shoulders:	Median + Outside
Protective barriers:	Med. (Concrete) + Out. (Concrete)
Number of vehicles involved in accident:	4
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Med. Shl.	8:04	8:40	36	Veh.	Minor
Med. Shl.	8:40	9:30	40	Veh. Pol. Tow	Minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Police	8:40	Reg. Dir. Main Lanes	9:30
Tow	8:40	Reg. Dir. Main Lanes	9:06

San Antonio. Accident # 35.

Accident #	35
Tape #	9
Day	5/26/00
Camera I.D.	US 281 N at the River
Time when accident reported:	13:05
Time when recording start:	13:07
Time when recording finished:	13:59
Number of traffic lanes in one direction:	4
Shoulders:	outside + median
Protective barriers:	Med. (concretel) + Out. (metal)
Number of vehicles involved in accident:	2
Traffic lane where accidents happened:	4

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Out. Shl.	13:05	13:41	36	Veh.	Minor
Out. Shl.	13:41	13:59	18	Veh., Pol.	Minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Police	13:41	Reg. Dir. Main Lanes	13:58

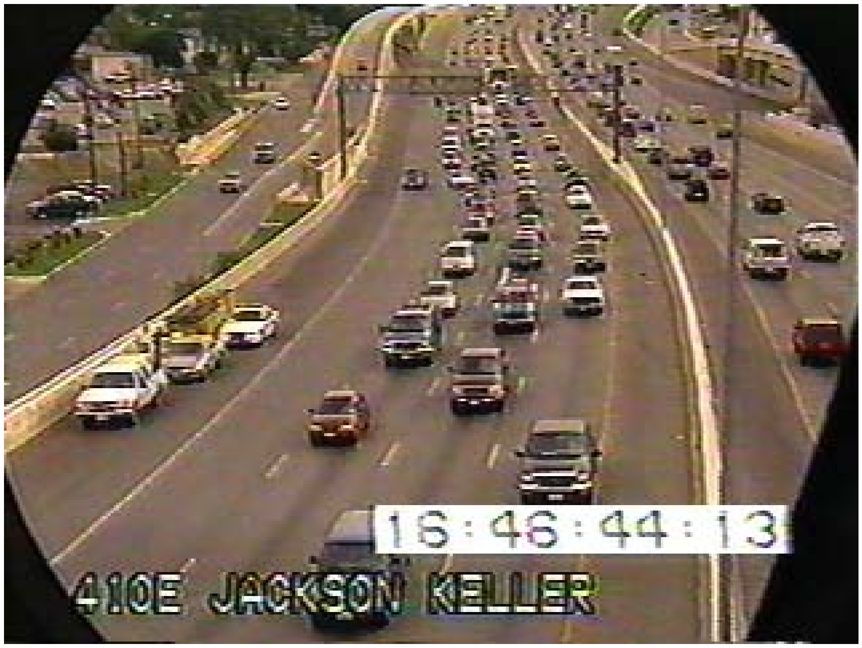
San Antonio. Accident # 36.

Accident #	36
Tape #	9
Day	5/26/00
Camera I.D.	LP 410E Jackson Keller
Time when accident reported:	~15:15
Time when recording start:	15:25
Time when recording finished:	15:49
Number of traffic lanes in one direction:	3 + Ramp (Entrance)
Shoulders:	Median
Protective barriers:	Median (concrete)
Number of vehicles involved in accident:	3
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Med. Shl.	15:15	15:25	10	Veh.	Minor
Med. Shl.	15:25	15:41	16	Veh. Pol.	Minor
1 + Med. Shl.	15:41	15:42	1	Veh. Pol. Tow	Major
Med. Shl.	15:42	15:48	6	Veh. Pol. Tow	Major

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Police 1	15:25	Reg. Dir. Main Lanes	15:48
Police 2	15:25	Reg. Dir. Main Lanes	15:48
Tow 1	15:41	Reg. Dir. Main Lanes	15:48
Tow 2	15:41	Reg. Dir. Main Lanes	15:47

San Antonio. Accident # 37.



Accident #	37
Tape #	9
Day	5/26/00
Camera I.D.	LP 410E Jackson Keller
Time when recording start:	16:46
Time when recording finished:	17:04
Number of traffic lanes in one direction:	4
Shoulders:	Median + Outside
Protective barriers:	Med. (concrete) + Out. (concrete)
Number of vehicles involved in accident:	2
Traffic lane where accidents happened:	4

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
Out. Shl.	16:46	17:04	18	Veh. Pol.	Minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Police	16:46	Reg. Dir. Main Lanes	17:04

San Antonio. Accident # 38.

Accident #	38
Tape #	9
Day	5/26/00
Camera I.D.	I 35N at Flores
Time when accident reported:	13:44
Time when recording start:	13:46
Time when recording finished:	14:09
Number of traffic lanes in one direction:	3 + Ramp (Exit)
Shoulders:	Median + Outside
Protective barriers:	Med. (concrete) + Out. (concrete)
Number of vehicles involved in accident:	2
Traffic lane where accidents happened:	Ramp Exit Lane

Blockage					Influence on traffic
Lane (s)	Time From	Time To	Duration, min.	Reason for blockage	
Ramp (Exit)	13:44	13:48	4	Veh.	Minor
Ramp (Exit)	13:48	14:07	19	Veh. Pol. Tow	Minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Police	13:48	Reg. Dir. Main Lanes	14:07
Tow	13:56	Reg. Dir. Main Lanes	14:07

San Antonio. Accident # 39.

Accident #	39
Tape #	9
Day	5/26/00
Camera I.D.	LP 410W at Cherryridge
Time when recording start:	14:56
Time when recording finished:	15:34
Number of traffic lanes in one direction:	4
Shoulders:	Median + Outside
Protective barriers:	Med. (concrete) + Out. (concrete)
Number of vehicles involved in accident:	2
Traffic lane where accidents happened:	4

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
4	14:56	15:02	6	Veh.	Medium
4	15:02	15:05	3	Veh. Pol. Amb.	Medium
4 + Out. Shl.	15:05	15:16	9	Veh. Pol. Amb. Tow	Major
Out. Shl.	15:16	15:34	18	Veh. Pol. Tow	Minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Police 1	15:02	Reg. Dir. Main Lanes	15:16
Ambulance	15:05	Reg. Dir. Main Lanes + Out. Shl.	15:09
Tow	15:07	Reg. Dir. Main Lanes + Out. Shl.	15:28
Police 2	15:05	Reg. Dir. Main Lanes + Out. Shl.	15:34

San Antonio. Accident # 40.

Accident #	40
Tape #	9
Day	5/26/00
Camera I.D.	LP 410E Fredericksburg
Time when accident reported:	17:14
Time when recording start:	17:17
Time when recording finished:	18:17
Number of traffic lanes in one direction:	3
Shoulders:	Median + Outside
Protective barriers:	Med. (concrete)
Number of vehicles involved in accident:	2
Traffic lane where accidents happened:	1

Blockage					Influence on traffic
Lane (s)	Time		Duration, min.	Reason for blockage	
	From	To			
1 + Shl.(med.)	17:14	17:17	3	veh.	major
1 + Shl.(med.)	17:17	18:05	48	veh.,ambul.,pol.	major
Shl.(med.)	18:05	18:16	11	veh.	minor

Emergency vehicle type	Emergency vehicles arriving time	Emergency vehicles arrived by	Emergency vehicles departure time
Ambulance	17:17	Reg. Dir. Main Lanes	17:32
Police 1	17:17	Opp. Dir. Main Lanes	17:29
Police 2	17:20	Opp. Dir. Main Lanes	18:17
Fire	17:22	Reg. Dir. Main Lanes	17:24
Police 3	17:28	Reg. Dir. Main Lanes	18:05
Tow	17:46	Reg. Dir. Main Lanes	18:02

APPENDIX C

Accident Characteristics

Accident Characteristics: Houston

Accident characteristics. Houston																														
Accident #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
I. Fraction of cases where accidents occurred by different traffic lanes																														
Accident location	right	right	left	n/a	n/a	left	right	center	center	left	n/a	right	n/a	left	right	left	right	n/a	left	left	left	left	left	left	left	right	center	left	right	center
II-a. Duration of blockage (actual time), minute																														
total time	18	4	5	56	44	26	30	4	18	20	23	43	28	40	10	46	22	23	37	29	12	12	13	16	71	10	6	23	21	14
right	18	4	0	56	0	0	30	1	0	0	1	43	0	0	10	0	22	0	3	0	2	0	0	2	4	10	0	0	21	1
center	0	0	0	0	0	0	0	3	18	0	0	43	0	0	0	0	2	0	25	0	2	1	0	2	1	2	6	0	0	13
left	0	0	5	0	0	26	0	1	0	20	22	8	28	40	0	46	0	23	34	29	12	12	13	16	71	2	0	23	0	0
all lanes	0	0	0	0	44	0	0	0	0	0	1	8	3	0	0	0	0	0	4	0	2	0	0	2	4	2	0	0	0	0
II-b. Duration of blockage (percentage of total blockage duration), percent																														
right	100.0	100.0	0.0	100.0	0.0	0.0	100.0	25.0	0.0	0.0	4.3	100.0	0.0	0.0	100.0	0.0	100.0	0.0	8.1	0.0	16.7	0.0	0.0	12.5	5.6	100.0	0.0	0.0	100.0	7.1
center	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	100.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	9.1	0.0	67.6	0.0	16.7	8.3	0.0	12.5	1.4	20.0	100.0	0.0	0.0	92.9
left	0.0	0.0	100.0	0.0	0.0	100.0	0.0	25.0	0.0	100.0	95.7	18.6	100.0	100.0	0.0	100.0	0.0	100.0	91.9	100.0	100.0	100.0	100.0	100.0	100.0	20.0	0.0	100.0	0.0	0.0
all lanes	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	4.3	18.6	10.7	0.0	0.0	0.0	0.0	0.0	10.8	0.0	16.7	0.0	0.0	12.5	5.6	20.0	0.0	0.0	0.0	0.0
III. Fraction of cases where all lanes were blocked at some time																														
All lane blockage	no	no	no	n/a	n/a	no	no	no	no	no	n/a	yes	yes	no	no	no	no	n/a	yes	no	yes	no	no	yes	yes	yes	no	no	no	no
IV-a. Duration of influence on traffic (actual time), minute																														
minor	10	4	0	0	0	0	0	1	0	20	0	0	0	5	10	46	0	0	1	0	2	0	6	0	0	7	0	1	21	11
medium	1	0	5	56	0	26	8	3	18	0	22	0	0	35	0	0	20	18	0	29	8	0	3	11	0	0	6	8	0	3
major	7	0	0	0	0	0	22	0	0	0	0	35	25	0	0	0	2	0	32	0	0	12	4	3	67	1	0	14	0	0
traffic blocked	0	0	0	0	44	0	0	0	0	0	1	8	3	0	0	0	0	0	4	0	2	0	0	2	4	2	0	0	0	0
IV-b. Duration of influence on traffic (percentage of total blockage duration), percent																														
minor	55.6	100.0	0.0	0.0	0.0	0.0	0.0	25.0	0.0	100.0	0.0	0.0	0.0	12.5	100.0	100.0	0.0	0.0	2.7	0.0	16.7	0.0	46.2	0.0	0.0	70.0	0.0	4.3	100.0	78.6
medium	5.6	0.0	100.0	100.0	0.0	100.0	26.7	75.0	100.0	0.0	95.7	0.0	0.0	87.5	0.0	0.0	90.9	78.3	0.0	100.0	66.7	0.0	23.1	68.8	0.0	0.0	100.0	34.8	0.0	21.4
major	38.9	0.0	0.0	0.0	0.0	0.0	73.3	0.0	0.0	0.0	0.0	81.4	89.3	0.0	0.0	0.0	9.1	0.0	86.5	0.0	0.0	100.0	30.8	18.8	94.4	10.0	0.0	60.9	0.0	0.0
traffic blocked	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	4.3	18.6	10.7	0.0	0.0	0.0	0.0	0.0	10.8	0.0	16.7	0.0	0.0	12.5	5.6	20.0	0.0	0.0	0.0	0.0
V-a. Time during when emergency vehicles are present (actual time), minute																														
right	18	4	0	50	23	0	27	1	0	0	0	43	0	0	10	0	17	0	3	0	0	0	0	0	0	8	0	0	21	1
center	0	0	0	0	23	0	0	0	1	0	0	43	0	0	0	0	2	0	25	0	0	1	0	0	1	0	1	0	0	13
left	0	0	5	0	23	4	0	1	0	20	23	8	28	38	0	46	0	18	22	26	12	12	7	16	71	0	0	23	0	0
V-b. Time during when emergency vehicles are present (percentage of total blockage duration), percent																														
right	100.0	100.0	0.0	89.3	52.3	0.0	90.0	25.0	0.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	77.3	0.0	8.1	0.0	0.0	0.0	0.0	0.0	0.0	80.0	0.0	0.0	100.0	7.1
center	0.0	0.0	0.0	0.0	52.3	0.0	0.0	0.0	5.6	0.0	0.0	100.0	0.0	0.0	0.0	0.0	9.1	0.0	67.6	0.0	0.0	8.3	0.0	0.0	1.4	0.0	16.7	0.0	0.0	92.9
left	0.0	0.0	100.0	0.0	52.3	15.4	0.0	25.0	0.0	100.0	100.0	18.6	100.0	95.0	0.0	100.0	0.0	78.3	59.5	89.7	100.0	100.0	53.8	100.0	100.0	0.0	0.0	100.0	0.0	0.0

Accident Characteristics: San Antonio

Accident characteristics. San Antonio.

Accident #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
I. Fraction of cases where accidents occurred by different traffic lanes																				
Accident location	left	center	right	right	left	center	right	left	right	right	left	left	left	left	right	left	left	center	left	left
II-a. Duration of blockage (actual time), minute																				
total time	56	65	6	12	56	46	31	36	18	23	41	42	13	12	60	28	20	54	84	34
right	0	1	6	12	0	46	31	0	18	23	0	0	0	0	60	1	0	42	0	0
center	0	64	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	43	0	0
left	56	64	0	0	56	0	0	36	0	0	41	42	13	12	0	28	20	19	84	34
all lanes	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	15	0	0
II-b. Duration of blockage (percentage of total blockage duration), percent																				
right	0.0	1.5	100.0	100.0	0.0	100.0	100.0	0.0	100.0	100.0	0.0	0.0	0.0	0.0	100.0	3.6	0.0	77.8	0.0	0.0
center	0.0	98.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.6	0.0	79.6	0.0	0.0
left	100.0	98.5	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	100.0	100.0	100.0	0.0	100.0	100.0	35.2	100.0	100.0
all lanes	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.6	0.0	27.8	0.0	0.0
III. Fraction of cases where all lanes were blocked at some time																				
All lane blockage	no	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	yes	no	no
IV-a. Duration of influence on traffic (actual time), minute																				
minor	51	0	0	12	0	10	0	36	0	0	0	42	13	12	0	27	20	0	24	34
medium	5	0	0	0	21	17	0	0	18	21	0	0	0	0	0	0	0	0	18	0
major	0	64	6	0	35	18	31	0	0	2	41	0	0	0	0	0	0	39	42	0
traffic blocked	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	15	0	0
IV-b. Duration of influence on traffic (percentage of total blockage duration), percent																				
minor	91.1	0.0	0.0	100.0	0.0	21.7	0.0	100.0	0.0	0.0	0.0	100.0	100.0	100.0	0.0	96.4	100.0	0.0	28.6	100.0
medium	8.9	0.0	0.0	0.0	37.5	37.0	0.0	0.0	100.0	91.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.4	0.0
major	0.0	98.5	100.0	0.0	62.5	39.1	100.0	0.0	0.0	8.7	100.0	0.0	0.0	0.0	0.0	0.0	0.0	72.2	50.0	0.0
traffic blocked	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.6	0.0	27.8	0.0	0.0
V-a. Time during when emergency vehicles are present (actual time), minute																				
right	0	0	0	1	0	41	18	0	15	22	0	0	0	0	42	0	0	43	0	0
center	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	55	0	0
left	26	60	0	0	56	0	0	34	0	0	30	32	13	8	0	3	16	4	66	25
V-b. Time during when emergency vehicles are present (percentage of total blockage duration), percent																				
right	0.0	0.0	0.0	8.3	0.0	89.1	58.1	0.0	83.3	95.7	0.0	0.0	0.0	0.0	70.0	0.0	0.0	79.6	0.0	0.0
center	0.0	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.6	0.0	101.9	0.0	0.0
left	46.4	92.3	0.0	0.0	100.0	0.0	0.0	94.4	0.0	0.0	73.2	76.2	100.0	66.7	0.0	10.7	80.0	7.4	78.6	73.5

Accident #	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
I. Fraction of cases where accidents occurred by different traffic lanes																				
Accident location	right	left	right	right	right	right	left	left	right	right	right	right	left	left	right	left	right	right	right	left
II-a. Duration of blockage (actual time), minute																				
total time	21	7	53	36	20	65	24	50	34	40	35	31	40	76	54	33	18	23	36	62
right	21	0	53	36	20	65	0	0	34	40	35	31	0	0	54	0	18	23	36	0
center	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
left	0	7	0	0	0	0	24	50	0	0	0	0	39	76	0	33	0	0	0	62
all lanes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
II-b. Duration of blockage (percentage of total blockage duration), percent																				
right	100.0	0.0	100.0	100.0	100.0	100.0	0.0	0.0	100.0	100.0	100.0	100.0	0.0	0.0	100.0	0.0	100.0	100.0	100.0	0.0
center	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
left	0.0	100.0	0.0	0.0	0.0	0.0	100.0	100.0	0.0	0.0	0.0	0.0	97.5	100.0	0.0	100.0	0.0	0.0	0.0	100.0
all lanes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
III. Fraction of cases where all lanes were blocked at some time																				
All lane blockage	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
IV-a. Duration of influence on traffic (actual time), minute																				
minor	21	7	21	34	0	18	0	47	0	40	35	31	0	76	54	26	18	0	18	11
medium	0	0	17	2	0	26	0	3	0	0	0	0	0	0	0	0	0	23	9	0
major	0	0	15	0	0	0	24	0	34	0	0	0	40	0	0	7	0	0	9	51
traffic blocked	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IV-b. Duration of influence on traffic (percentage of total blockage duration), percent																				
minor	100.0	100.0	39.6	94.4	0.0	27.7	0.0	94.0	0.0	100.0	100.0	100.0	0.0	100.0	100.0	78.8	100.0	0.0	50.0	17.7
medium	0.0	0.0	32.1	5.6	0.0	40.0	0.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	25.0	0.0
major	0.0	0.0	28.3	0.0	0.0	0.0	100.0	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	21.2	0.0	0.0	25.0	82.3
traffic blocked	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
V-a. Time during when emergency vehicles are present (actual time), minute																				
right	10	0	45	27	0	50	0	0	34	33	28	29	0	0	18	0	18	19	30	0
center	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
left	0	7	0	0	0	0	24	40	0	0	0	0	34	40	0	23	0	0	0	59
V-b. Time during when emergency vehicles are present (percentage of total blockage duration), percent																				
right	47.6	0.0	84.9	75.0	0.0	76.9	0.0	0.0	100.0	82.5	80.0	93.5	0.0	0.0	33.3	0.0	100.0	82.6	83.3	0.0
center	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
left	0.0	100.0	0.0	0.0	0.0	0.0	100.0	80.0	0.0	0.0	0.0	0.0	85.0	52.6	0.0	69.7	0.0	0.0	0.0	95.2

APPENDIX D

Accident Data Analysis

Houston

Houston

I. Fraction of cases where accidents occurred by different traffic lanes.

All highways.

	Quantity	Percent
Right	8	32.00
Center	4	16.00
Left	13	52.00
Total	25	100.00

2-3 lanes, one-direction highways.

	Quantity	Percent
Right	3	33.33
Center	0	0.00
Left	6	66.67
Total	9	100.00

More than 3 lanes, one-direction highways.

	Quantity	Percent
Right	5	31.25
Center	4	25.00
Left	7	43.75
Total	16	100.00

Houston

II. Fraction of accidents with different roadway blockage.

Blockage location	All highways		2-3 lanes		more than 3 lanes	
	#	%	#	%	#	%
Right	14	56.00	4	57.14	10	55.56
Center	12	48.00	2	28.57	10	55.56
Left	16	64.00	5	71.43	11	61.11
All lanes	6	24.00	2	28.57	4	22.22
Total	25	100.00	7	100.00	18	100.00

Houston
III. Duration of blockage.

Actual time, minutes | **Percentage of total blockage duration, percent**

All highways.

	Right	Center	Left	All lanes
Minimum	0.00	0.00	0.00	0.00
Maximum	43.00	43.00	71.00	8.00
Mode	0.00	0.00	0.00	0.00
Mean	6.84	4.72	14.32	0.88
Standard Deviation	11.33	10.15	18.30	1.92
Variance	128.31	103.04	334.98	3.69

	Right	Center	Left	All lanes
Minimum	0.00	0.00	0.00	0.00
Maximum	100.00	100.00	100.00	100.00
Mode	0.00	0.00	100.00	0.00
Mean	35.00	24.14	54.22	3.37
Standard Deviation	45.91	38.32	48.44	6.60
Variance	2107.46	1468.17	2346.68	43.55

2 - 3 lanes, one-direction highways.

	Right	Center	Left	All lanes
Minimum	0.00	0.00	0.00	0.00
Maximum	30.00	25.00	40.00	4.00
Mode	0.00	0.00	0.00	0.00
Mean	7.57	3.86	17.14	0.86
Standard Deviation	11.80	9.35	16.88	1.57
Variance	139.29	87.48	284.81	2.48

	Right	Center	Left	All lanes
Minimum	0.00	0.00	0.00	0.00
Maximum	100.00	100.00	100.00	100.00
Mode	0.00	0.00	100.00	0.00
Mean	32.11	12.03	70.27	3.93
Standard Deviation	46.77	25.26	48.09	6.91
Variance	2187.64	638.25	2313.12	47.80

More than 3 lanes, one-direction highways.

	Right	Center	Left	All lanes
Minimum	0.00	0.00	0.00	0.00
Maximum	43.00	43.00	71.00	8.00
Mode	0.00	0.00	0.00	0.00
Mean	6.56	5.06	13.22	0.89
Standard Deviation	11.47	10.69	19.18	2.08
Variance	131.67	114.17	367.83	4.34

	Right	Center	Left	All lanes
Minimum	0.00	0.00	0.00	0.00
Maximum	100.00	100.00	100.00	100.00
Mode	0.00	0.00	100.00	0.00
Mean	36.13	28.84	47.98	3.15
Standard Deviation	46.89	42.00	48.47	6.67
Variance	2198.34	1763.67	2349.24	44.43

Houston

IV. Fraction of cases where all lanes were blocked at some time.

All highways.

	Quantity	Percent
Total	25	100.00
Accidents with all lanes blocked	6	24.00

2-3 lanes, one-direction highways.

	Quantity	Percent
Total	7	100.00
Accidents with all lanes blocked	2	28.57

More than 3 lanes, one-direction highways.

	Quantity	Percent
Total	18	100.00
Accidents with all lanes blocked	4	22.22

Houston
V. Duration of influence on traffic

Actual time, minutes **Percentage of total blockage duration, percent**

All highways.

	Minor	Medium	Major	Blocked			Minor	Medium	Major	Blocked
Minimum	0.00	0.00	0.00	0.00		Minimum	0.00	0.00	0.00	0.00
Maximum	46.00	35.00	67.00	8.00		Maximum	100.00	100.00	100.00	20.00
Mode	0.00	0.00	0.00	0.00		Mode	0.00	0.00	0.00	0.00
Mean	5.80	7.36	7.96	0.88		Mean	32.46	40.01	24.16	3.37
Standard Deviation	10.35	10.23	15.89	1.92		Standard Deviation	41.35	42.64	35.65	6.60
Variance	107.08	104.74	252.37	3.69		Variance	1709.76	1818.06	1270.67	43.55

2 - 3 lanes, one-direction highways.

	Minor	Medium	Major	Blocked			Minor	Medium	Major	Blocked
Minimum	0.00	0.00	0.00	0.00		Minimum	0.00	0.00	0.00	0.00
Maximum	10.00	35.00	32.00	4.00		Maximum	55.56	100.00	86.49	16.67
Mode	0.00	8.00	0.00	0.00		Mode	0.00	100.00	0.00	0.00
Mean	2.57	12.29	8.71	0.86		Mean	12.49	55.20	28.39	3.93
Standard Deviation	3.74	13.92	13.07	1.57		Standard Deviation	20.15	43.81	38.14	6.91
Variance	13.95	193.90	170.90	2.48		Variance	405.98	1919.10	1454.88	47.80

More than 3 lanes, one-direction highways.

	Minor	Medium	Major	Blocked			Minor	Medium	Major	Blocked
Minimum	0.00	0.00	0.00	0.00		Minimum	0.00	0.00	0.00	0.00
Maximum	46.00	26.00	67.00	8.00		Maximum	100.00	100.00	100.00	20.00
Mode	0.00	0.00	0.00	0.00		Mode	0.00	0.00	0.00	0.00
Mean	7.06	5.44	7.67	0.89		Mean	40.23	34.11	22.51	3.15
Standard Deviation	11.84	8.10	17.19	2.08		Standard Deviation	45.19	41.92	35.64	6.67
Variance	140.29	65.56	295.65	4.34		Variance	2042.40	1757.47	1270.17	44.43

Houston

VI. Time during which emergency vehicles are present.

Actual time, minutes | **Percentage of total blockage duration, percent**

All highways.

	Right	Center	Left			Right	Center	Left
Minimum	0.00	0.00	0.00		Minimum	0.00	0.00	0.00
Maximum	43.00	43.00	71.00		Maximum	100.00	100.00	100.00
Mode	0.00	0.00	0.00		Mode	0.00	0.00	0.00
Mean	6.12	3.48	12.44		Mean	31.50	12.06	46.28
Standard Deviation	10.97	9.89	17.70		Standard Deviation	43.97	28.88	46.17
Variance	120.28	97.84	313.34		Variance	1933.55	833.96	2131.85

2 - 3 lanes, one-direction highways.

	Right	Center	Left			Right	Center	Left
Minimum	0.00	0.00	0.00		Minimum	0.00	0.00	0.00
Maximum	27.00	25.00	38.00		Maximum	100.00	67.57	100.00
Mode	0.00	0.00	0.00		Mode	0.00	0.00	0.00
Mean	6.86	3.57	14.71		Mean	28.30	9.65	63.44
Standard Deviation	11.05	9.45	14.48		Standard Deviation	45.75	25.54	45.50
Variance	122.14	89.29	209.57		Variance	2093.18	652.20	2070.27

More than 3 lanes, one-direction highways.

	Right	Center	Left			Right	Center	Left
Minimum	0.00	0.00	0.00		Minimum	0.00	0.00	0.00
Maximum	43.00	43.00	71.00		Maximum	100.00	100.00	100.00
Mode	0.00	0.00	0.00		Mode	0.00	0.00	0.00
Mean	5.83	3.44	11.56		Mean	32.75	13.00	39.60
Standard Deviation	11.24	10.33	19.12		Standard Deviation	44.55	30.72	45.94
Variance	126.38	106.61	365.44		Variance	1985.09	943.85	2110.44

Houston

VII. Fraction of different emergency vehicles arriving approaches.

All highways.

Emergency vehicles arrived by:	Quantity	Percent
a) opposite direction main lanes	5	4.24
b) regular direction main lanes	85	72.03
c) frontage road	18	15.25
d) shoulder	6	5.09
e) others	4	3.39
Total	**118**	**100**

2 - 3 lanes, one-direction highways.

Emergency vehicles arrived by:	Quantity	Percent
a) opposite direction main lanes	1	2.86
b) regular direction main lanes	26	74.29
c) frontage road	2	5.71
d) shoulder	2	5.71
e) others	4	11.43
Total	**35**	**100**

More than 3 lanes, one-direction highways.

Emergency vehicles arrived by:	Quantity	Percent
a) opposite direction main lanes	4	6.35
b) regular direction main lanes	53	84.13
c) frontage road	2	3.17
d) shoulder	4	6.35
e) others	0	0
Total	**63**	**100**

APPENDIX E

Accident Data Analysis

San Antonio

San Antonio

I. Fraction of cases where accidents occurred by different traffic lanes.

All highways.

	Quantity	Percent
Right	19	47.50
Center	3	7.50
Left	18	45.00
Total	40	100.00

2-3 lanes, one-direction highways.

	Quantity	Percent
Right	12	42.86
Center	1	3.57
Left	15	53.57
Total	28	100.00

More than 3 lanes, one-direction highways.

	Quantity	Percent
Right	7	58.33
Center	2	16.67
Left	3	25.00
Total	12	100.00

San Antonio

II. Fraction of accidents with different roadway blockage.

Blockage location	All highways		2-3 lanes		More than 3 lanes	
	#	%	#	%	#	%
Right	21	55.26	12	46.15	9	75.00
Center	4	10.53	3	11.54	1	8.33
Left	20	52.63	16	61.54	4	33.33
All lanes	3	7.89	2	7.69	1	8.33
Total	38	100.00	26	100.00	12	100.00

San Antonio
III. Duration of blockage.

Actual time, minutes | **Percentage of total blockage duration, percent**

All highways.

	Right	Center	Left	All lanes			Right	Center	Left	All lanes
Minimum	0.00	0.00	0.00	0.00		Minimum	0.00	0.00	0.00	0.00
Maximum	65.00	64.00	84.00	15.00		Maximum	100.00	100.00	100.00	100.00
Mode	0.00	0.00	0.00	0.00		Mode	100.00	0.00	0.00	0.00
Mean	16.47	2.87	20.95	0.45		Mean	49.55	4.85	50.82	0.87
Standard Deviation	19.69	12.34	25.39	2.44		Standard Deviation	50.07	20.24	49.95	4.53
Variance	387.61	152.28	644.86	5.93		Variance	2507.24	409.78	2494.56	20.49

2 - 3 lanes, one-direction highways.

	Right	Center	Left	All lanes			Right	Center	Left	All lanes
Minimum	0.00	0.00	0.00	0.00		Minimum	0.00	0.00	0.00	0.00
Maximum	65.00	43.00	84.00	15.00		Maximum	100.00	100.00	100.00	100.00
Mode	0.00	0.00	0.00	0.00		Mode	0.00	0.00	100.00	0.00
Mean	12.96	1.73	22.54	0.62		Mean	41.59	3.30	58.95	1.21
Standard Deviation	18.96	8.42	24.50	2.94		Standard Deviation	49.43	15.59	49.15	5.46
Variance	359.32	70.92	600.10	8.65		Variance	2443.54	243.10	2415.73	29.86

More than 3 lanes, one-direction highways.

	Right	Center	Left	All lanes			Right	Center	Left	All lanes
Minimum	0.00	0.00	0.00	0.00		Minimum	0.00	0.00	0.00	0.00
Maximum	54.00	64.00	76.00	1.00		Maximum	100.00	100.00	100.00	100.00
Mode	0.00	0.00	0.00	0.00		Mode	100.00	0.00	0.00	0.00
Mean	24.08	5.33	17.50	0.08		Mean	66.79	8.21	33.21	0.13
Standard Deviation	19.87	18.48	28.04	0.29		Standard Deviation	49.05	28.42	49.05	0.44
Variance	394.81	341.33	786.27	0.08		Variance	2405.79	807.89	2405.79	0.20

San Antonio

IV. Fraction of cases where all lanes were blocked at some time.

All highways.

	Quantity	Percent
Total	38	100.00
Accidents with all lanes blocked	3	7.89

2-3 lanes, one-direction highways.

	Quantity	Percent
Total	26	100.00
Accidents with all lanes blocked	2	7.69

More than 3 lanes, one-direction highways.

	Quantity	Percent
Total	12	100.00
Accidents with all lanes blocked	1	8.33

San Antonio
V. Duration of influence on traffic.

Actual time, minutes | **Percentage of total blockage duration, percent**

All highways.

	Minor	Medium	Major	Blocked
Minimum	0.00	0.00	0.00	0.00
Maximum	76.00	26.00	64.00	15.00
Mode	0.00	0.00	0.00	0.00
Mean	19.42	4.74	12.05	0.45
Standard Deviation	18.95	8.35	18.29	2.44
Variance	359.17	69.71	334.59	5.93

	Minor	Medium	Major	Blocked
Minimum	0.00	0.00	0.00	0.00
Maximum	100.00	100.00	100.00	27.78
Mode	100.00	0.00	0.00	0.00
Mean	56.32	13.28	28.63	0.87
Standard Deviation	45.76	27.64	40.41	4.53
Variance	2093.76	763.88	1633.17	20.49

2 - 3 lanes, one-direction highways.

	Minor	Medium	Major	Blocked
Minimum	0.00	0.00	0.00	0.00
Maximum	51.00	26.00	51.00	15.00
Mode	0.00	0.00	0.00	0.00
Mean	14.73	5.04	14.04	0.62
Standard Deviation	15.63	8.85	18.19	2.94
Variance	244.28	78.28	330.84	8.65

	Minor	Medium	Major	Blocked
Minimum	0.00	0.00	0.00	0.00
Maximum	100.00	100.00	100.00	27.78
Mode	0.00	0.00	0.00	0.00
Mean	49.00	13.31	35.25	1.21
Standard Deviation	46.34	28.29	43.51	5.46
Variance	2147.45	800.29	1893.34	29.86

More than 3 lanes, one-direction highways.

	Minor	Medium	Major	Blocked
Minimum	0.00	0.00	0.00	0.00
Maximum	76.00	21.00	64.00	1.00
Mode	0.00	0.00	0.00	0.00
Mean	29.58	4.08	7.75	0.08
Standard Deviation	22.10	7.48	18.55	0.29
Variance	488.27	55.90	344.02	0.08

	Minor	Medium	Major	Blocked
Minimum	0.00	0.00	0.00	0.00
Maximum	100.00	91.30	98.46	1.54
Mode	100.00	0.00	0.00	0.00
Mean	72.18	13.23	14.27	0.13
Standard Deviation	41.96	27.40	29.36	0.44
Variance	1760.86	750.57	861.96	0.20

San Antonio

VI. Time during which emergency vehicles are present.

Actual time, minutes | **Percentage of total blockage duration, percent**

All highways.

	Right	Center	Left			Right	Center	Left
Minimum	0.00	0.00	0.00		Minimum	0.00	0.00	0.00
Maximum	50.00	55.00	66.00		Maximum	100.00	101.85	100.00
Mode	0.00	0.00	0.00		Mode	0.00	0.00	0.00
Mean	12.66	1.53	15.79		Mean	35.63	2.86	39.00
Standard Deviation	16.11	8.92	20.47		Standard Deviation	41.41	16.51	42.19
Variance	259.69	79.50	419.04		Variance	1714.51	272.60	1780.16

2 - 3 lanes, one-direction highways.

	Right	Center	Left			Right	Center	Left
Minimum	0.00	0.00	0.00		Minimum	0.00	0.00	0.00
Maximum	50.00	55.00	66.00		Maximum	100.00	101.85	100.00
Mode	0.00	0.00	0.00		Mode	0.00	0.00	0.00
Mean	10.15	2.15	16.96		Mean	27.50	4.05	44.96
Standard Deviation	16.37	10.78	20.51		Standard Deviation	39.01	19.96	42.65
Variance	268.06	116.22	420.68		Variance	1521.39	398.36	1819.19

More than 3 lanes, one-direction highways.

	Right	Center	Left			Right	Center	Left
Minimum	0.00	0.00	0.00		Minimum	0.00	0.00	0.00
Maximum	41.00	2.00	60.00		Maximum	100.00	3.08	94.44
Mode	0.00	0.00	0.00		Mode	0.00	0.00	0.00
Mean	18.08	0.17	13.25		Mean	53.25	0.26	26.08
Standard Deviation	14.74	0.58	21.05		Standard Deviation	42.60	0.89	39.84
Variance	217.36	0.33	443.11		Variance	1814.46	0.79	1587.05

San Antonio

VII. Fraction of different emergency vehicles arriving approaches.

All highways.

Emergency vehicles arrived by:	Quantity	Percent
a) opposite direction main lanes	7	5.34
b) regular direction main lanes	107	80.45
c) frontage road	1	0.76
d) shoulder	15	11.45
e) others	3	2.29
Total	**133**	**100**

2 - 3 lanes, one-direction highways.

Emergency vehicles arrived by:	Quantity	Percent
a) opposite direction main lanes	6	6.74
b) regular direction main lanes	71	78.02
c) frontage road	1	1.12
d) shoulder	10	11.24
e) others	3	3.37
Total	**91**	**100.49**

More than 3 lanes, one-direction highways.

Emergency vehicles arrived by:	Quantity	Percent
a) opposite direction main lanes	1	2.38
b) regular direction main lanes	36	85.71
c) frontage road	0	0
d) shoulder	5	11.9
e) others	0	0
Total	**42**	**100**