Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-97/1467-2		

4. Title and Subtitle	5. Report Date
TRAFFIC MANAGEMENT SYSTEM CONSIDERATIONS IN FREEWAY DESIGN AND REDESIGN	March 1996 Revised: July 1996
	6. Performing Organization Code
7. Author(s) Gerald L. Ullman	8. Performing Organization Report No. Research Report 1467-2
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Study No. 0-1467
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Interim: September 1994-August 1995 14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.
Research Project Title: Highway Operations Research and Implementation

16. Abstract

This report describes some of the major issues relating to traffic management system components that should be addressed during preliminary and final freeway design or redesign/reconstruction. Items discussed include the location and design of the data communications trunk line, closed-circuit television camera placement, changeable message signs and lane control signal considerations, and freeway design features affecting ramp metering and incident response. Guidelines are presented to assist transportation agencies in coordinating the design of physical freeway elements with the design of various components of a freeway traffic management system.

17. Key Words	18. Distribution Statement
Freeway Traffic Management Systems, Freeway Design, Freeway Redesign and Reconstruction	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	62	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

IMPLEMENTATION STATEMENT

A few practical recommendations arose out of the performance of this research. Those suggested for immediate implementation are the following:

- Optimum locations for buried data communications trunk lines are in the separation between the freeway and frontage road or under the shoulder of the freeway. Designers should avoid running the trunk line longitudinally between the frontage road and right-of-way line or under the mainlanes of the freeway. Locations of buried trunk lines should be clearly marked above ground and in the ground above the conduit to avoid accidental breakage.

- Traffic management system designers should guard against information overload. This is accomplished by limiting the number of freeway guide sign panels displayed on the same overhead sign bridge that supports a changeable message sign or lane control signals. Generally speaking, no more than one guide sign panel should be installed on the sign bridge supporting a changeable message sign, and no more than two panels should be installed on bridges supporting a full array of lane control signals. Adequate spacing between sign bridges (i.e., 240 meters) that provides sufficient decision and reaction time should be maintained as well. This spacing should be maintained between changeable message signs and large guide signs as well.

The summary section of the report presents other recommendations regarding the data communications trunk line, closed-circuit television camera placement, vehicle detectors, and other traffic management system components.

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation or the Federal Highway Administration. The report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of the report preparation was Dr. Gerald L. Ullman (Texas P.E. registration #66876).

ACKNOWLEDGMENT

This study was conducted in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. Dr. Thomas Urbanik II of the Texas Transportation Institute served as the study supervisor. The author would like to thank Mr. Eddie Gutierez of the Texas Department of Transportation for his insight and guidance as the task advisor for this research activity. The author would also like to acknowledge the many transportation professionals from the Texas Department of Transportation and other agencies who provided information during the data collection portion of this study. In particular, the contributions of Messrs. Abed Abukar (Fort Worth), Carlton Allen (Houston), Carlos Chavez (El Paso), Pat McGowan (San Antonio), Tai Nguyen (Fort Worth), Andy Oberlander (Dallas), and Ken Paradowski (Houston) of the Texas Department of Transportation are greatly appreciated.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

The purpose of this report is to highlight how freeway traffic management components can be better accommodated in the design or redesign/reconstruction phase of freeways. Through discussions with various traffic management officials and vendors of different types of traffic management components, it is evident that the anticipated implementation of traffic management system components affects several freeway design decisions. To achieve an efficient operational roadway system, designers need to be aware of the interdependence between various design elements and these various traffic management system components.

This report also presents guidance on the design of the various traffic management system components themselves and how they should relate to physical characteristics of the freeway. Included in this report are such topics as the location and physical design features of the data communications trunk line, freeway geometric features to consider when determining appropriate closed-circuit television camera locations, and design criteria for accident investigation sites.

1. INTRODUCTION

Many transportation agencies now consider the traditionally-separate functions of roadway planning, design, operations, and maintenance as an integrated process with the goal of achieving a properly functioning roadway system. These agencies recognize that many roadway planning and design decisions have a dramatic impact on how the roadway will operate in the future as well as the amount and type of maintenance that the roadway will require throughout its service life. Conversely, the goals and objectives for operating a roadway have a bearing on the planning and design decisions for that roadway.

Transportation agencies in many urban areas are turning to various traffic management tools and techniques (traffic surveillance and control systems, incident management programs and techniques, motorist information systems, etc.) to help mitigate the increasing traffic demands and traffic congestion that degrade freeway operations. As many freeways near the end of their service life and are redesigned and reconstructed, an excellent opportunity exists to match these design decisions with the traffic management tools and techniques that are scheduled or anticipated to be implemented on that freeway in the future. Unfortunately, only limited guidance is currently available as to how to best accomplish this match, or perhaps more accurately, how to make freeway designs more traffic management "friendly." Design information concerning the traffic management components themselves and how they should relate to the redesign of the freeway is often lacking. However, the experiences of those who have already gone through the design process can serve as a valuable source of information for those undertaking these activities.

FREEWAY FINAL DESIGN ELEMENTS

The final design stage of a freeway reconstruction is characterized by the preparation of construction plans and the determination of such design features as:

- superelevation runoff,
- drainage structure sizes,
- plan details,

- barriers and guardrails,
- signs (type and location),
- pavement markings, and
- curb type (if any).

With respect to traffic management techniques, hardware details such as loop detector placement, ground box locations, and communication trunk line conduit installation have typically been specified in this phase. Generally speaking, the more sensitive details such as the communication line design itself, computer equipment, electronic signs and signals, cameras, etc. have typically been addressed under a separate traffic management contract so that those contractors with expertise regarding traffic management component design and installation can be awarded a job separate from the general contractor who obtains the regular roadway construction job.

OBJECTIVE AND SCOPE OF THIS REPORT

The objective of the research documented in this report was to identify those freeway design features that influence the installation and operation of elements of a freeway traffic management system and to consolidate any experience and criteria that have been developed to help integrate traffic management needs into the freeway redesign process. The information contained herein was obtained through telephone and personal interviews with the following:

- several traffic management officials within the Texas Department of Transportation (TxDOT) District offices that have recently installed freeway traffic management systems or are planning to in the near future,

- vendors and users of video imaging, radar detection, electronic toll and traffic management, and changeable message sign technology, and

- selected officials from outside of the state of Texas who have also installed traffic management system components of one type or another.

The focus of the interviews was to identify the issues and concerns that have been encountered when installing these traffic management systems, emphasizing those problems that were a result of some aspect of freeway design. The interview data were then supplemented with published literature relating to various traffic management components or freeway design and operations. The emphasis of these efforts has been on considerations of traffic management system components during final freeway design. However, a number of decisions made during project development and preliminary design also impact the usefulness of certain traffic management elements. These are also discussed within this report.

This report consists of three more chapters. In Chapter 2, major issues that affect or relate to freeway design are discussed for each of the following traffic management system components:

- data communications trunk lines,
- closed-circuit television (CCTV) surveillance,
- vehicle detectors,
- ramp metering,
- changeable message signs and lane control signals, and
- incident management and response programs.

A set of guidelines for incorporating these various components into freeway redesign/reconstruction follows as Chapter 3 of this report. The report concludes with a final chapter that summarizes the issues and guidelines and emphasizes those findings suggested for immediate implementation.

2. TRAFFIC MANAGEMENT ELEMENT CONSIDERATIONS IN FREEWAY DESIGN

DATA COMMUNICATIONS TRUNK LINE ISSUES

Discussion with transportation agency personnel regarding the incorporation of surveillance and control data communications lines into the design of a freeway raised two major issues. The first issue related to the best physical location for the communications trunk line itself in the freeway right-of-way. The second issue related to the provision of trunk line conduit at the frontage road signalized intersections at major cross-street arterials.

Trunk Line Location

Most traffic management and control elements require a communications system to transfer information from the field equipment to a traffic operations center where it can be analyzed and interpreted. In addition, the communications system may also be required to transfer instructions from the operations center to the field equipment to execute an action. A large number of options exist for designing a communications system (e.g., its overall architecture, the hardware used, etc.). However, one of the most important decisions with respect to freeway design is the physical location of the communications line within the roadway right-of-way.

Several officials commented that the trunk line should not be placed in the outer separation between the frontage road and the edge of the right-of-way because driveway cuts and other work that occur in this area increase the risk of damage to the line. Also, the trunk line should not be placed under the freeway travel lanes longitudinally because of the potential disruption to traffic flow that would occur if the line required repairs. Consequently, data communications trunk lines are typically buried in conduit in the separation between the freeway and frontage road or under the paved shoulder of the freeway, or placed in the freeway median (i.e., in a metal rail mounted on top of the concrete barrier).

In past reconstruction projects, running a second or third cable through the buried conduit after an initial cable had already been pulled caused problems. This initial cable tended to bind at points within the conduit and hindered the installation of future cables. To combat this, a large conduit was fitted with smaller innerducts, one or more of which was left empty until needed at a future date. The Fort Worth District, for example, uses a 102-millimeter diameter PVC outer conduit with four 32-millimeter PVC innerducts for its communications line.

An alternative to underground conduit is to place communications on top of the center concrete median barrier in a metal barrier rail. The San Antonio District utilizes this approach. For this approach to be feasible, all of the various components in the system (CCTV, loop detectors, changeable message signs, lane control signals, highway advisory radio, etc.) should be accessible from the communications trunk line in the median without having to bore under the freeway. For example, the San Antonio District places most of their above-ground traffic management components on overhead sign bridges that are anchored on the median barrier. Communications cabling is run up the side of the structure and over to the components quite easily. Furthermore, extra cable is stored in these sign structure supports for repairs in the event of cable breakage.

The durability of such above-ground installations is unknown at this time. The effect of the rail upon the crashworthiness of the barrier is also not known. The San Antonio District only envisions their communications cable being damaged when semi-tractor trucks impact and destroy a section of the barrier. Furthermore, they have designed redundancy into their system so that they can still communicate with the various components of the system even if a break does occur. Vandalism of a top-mounted barrier rail may be a concern in some areas of the state, depending on traffic, pedestrian, and geometric characteristics. Aesthetics are another concern with respect to top-mounted barrier rails. Rails should be designed so as to blend in with the natural appearance of the barrier.

Data Communications at Frontage Road Intersections

Officials in several districts agree that any frontage road intersection reconstruction should include conduits placed underneath all intersection approaches, even if no communications cabling is envisioned. The cost of the small amount of extra conduit is small (generally less than $10,000 per intersection) compared to the extra cost, time, and difficulty of having to bore under the approaches to install conduit and cable at a later date.

CLOSED-CIRCUIT TELEVISION (CCTV) PLACEMENT AND OPERATIONAL ISSUES

CCTV is a major component of several freeway surveillance and control systems nationwide. With full pan, tilt, and zoom capabilities, CCTV is a versatile tool that allows system operators to monitor roadway conditions, verify reported or detected incidents, verify the display of changeable message sign information, identify the sources and consequences of congestion problems, and decide upon proper response actions during incident conditions. Current practices involve placing CCTV at approximately 1.6-kilometer intervals along the freeway. With a 10:1 standard zoom lens (the Ft. Worth District has found a 160:16 mm lens works best for them), full coverage of the freeway system is possible as long as the camera's view is not obstructed.

Unfortunately, the primary difficulty with CCTV implementation as it relates to freeway design is the ability to see all parts of the roadway within the viewing range of a camera installation. The freeway design characteristics that affect camera vision include the following:

- vertical alignment,
- cross-street bridges and interchange ramps,
- horizontal alignment (which results in obstructions by roadside signing, billboards, tall trees and buildings),
- freeway guide signing, and
- camera stability.

Each of these issues is discussed below.

Vertical Alignment

Vertical alignment visibility problems are typically experienced on older urban freeways where the freeway was carried over the cross-street arterials, creating a roller-coaster appearance (see Figure 1). Depending on the changes in elevation and other factors, this roller-coaster alignment can hide sizeable sections of freeway on crests away from the camera. More recent designs that utilize longer crest and sag curve lengths and fewer overpasses reduce the effect of vertical alignment on CCTV visibility of the freeway.

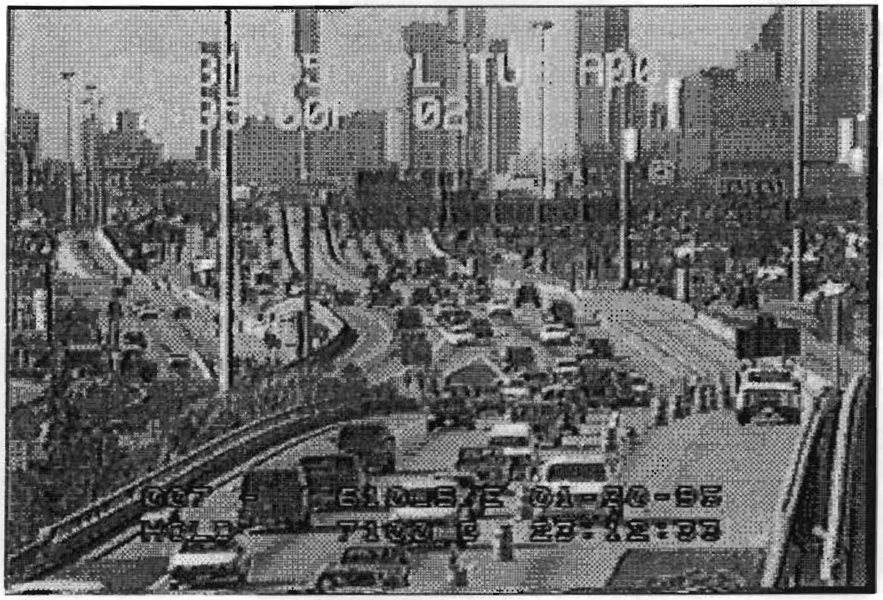


FIGURE 1. Example of Roller-Coaster Freeway Design

Cross-Street Bridges and Interchange Ramps

As shown in Figure 2, other visibility difficulties are created when a cross-street arterial or intersecting freeway and its ramps are taken over the freeway. Although it is sometimes possible to adjust where these obstructions occur, it is more likely that the design of the CCTV system itself will have to include additional cameras at other than the typical 1.6-kilometer spacing in order to adequately view the freeway in the region of these obstructions.

In addition to bridges and ramps that cross the freeway laterally and obstruct CCTV vision, longitudinal obstructions such as HOV lane retrofits can also severely limit CCTV viewing for the side of the freeway away from the camera (see Figure 3). Freeway cross-street overpasses also represent longitudinal obstructions to the view of the far-side frontage road intersections. Whereas older traffic management system designs tended to focus solely on the operation of the freeways, recent emphasis has been on the coordinated operations of all roadway facilities in a corridor or region. Given that accidents or other problems at frontage road intersections can cause vehicles to queue onto the freeway, the ability to see these intersections with the CCTV becomes a fairly high priority for system operators and should be considered during CCTV placement.

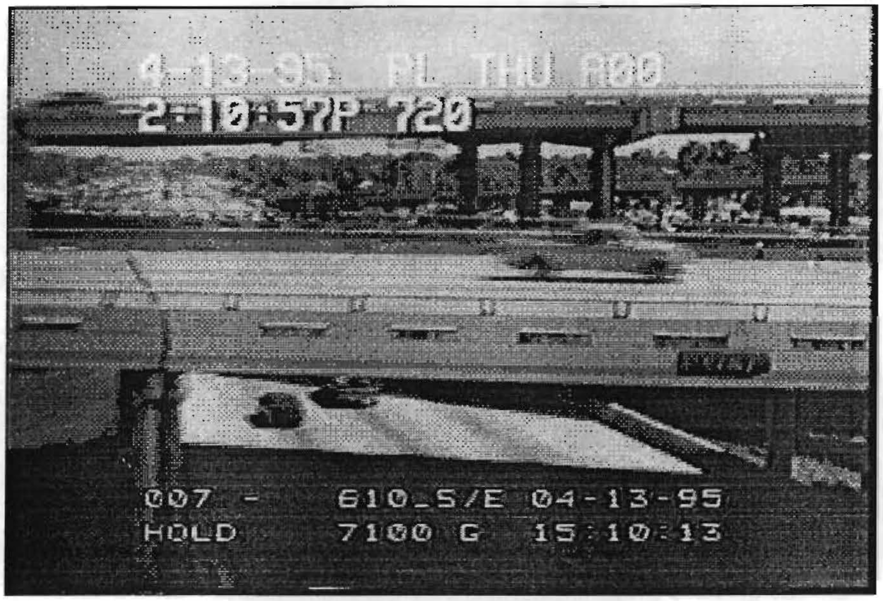


FIGURE 2. Effect of Crossing Freeway on CCTV View

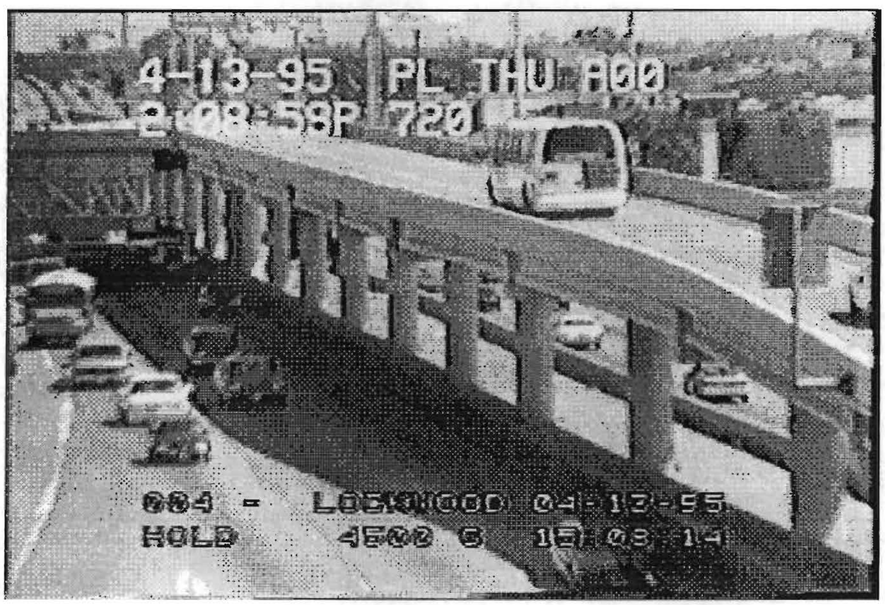


FIGURE 3. HOV Lane T-Ramp Blocking View of Far-Side Freeway Lanes

Horizontal Alignment

The horizontal alignment of the freeway can also create CCTV visibility problems. Generally speaking, the problem is not with the actual freeway layout itself, but with the roadside development that occurs adjacent to the freeway. Potential obstructions include billboard signing as well as buildings. Although existing obstructions can usually be identified at the time of CCTV installation through actual field inspections (*1*), future roadside development could cause difficulties with the field of view if these are not considered at the time of traffic management system design. In addition, the curvature of the roadway can cause shoulder-mounted guide signs to have an even greater view-blocking effect than on a section of straight freeway (these effects are discussed further in the next section).

Freeway Guide Signing

Another category of freeway design/redesign issues with respect to CCTV viewing relates to freeway guide signing layout. The impact of guide sign placement upon CCTV operations should be considered not only as part of a freeway redesign or reconstruction, but also any other time a change in the guide sign system is being contemplated. Both full-span overhead sign bridges as well as shoulder-mounted sign panels can obscure the view of CCTV. Figures 4 and 5 illustrate how both of these types of signs can obstruct a significant portion of the freeway scene. The degree to which a sign panel array at a location actually occludes freeway visibility is a function of camera height and lateral position from the freeway, sign panel size, sign mounting height, and distance of the sign array from the CCTV camera installation.

The geometric relationships defining camera view blockage by a sign array are illustrated in the appendix of this report. The roadway area obstructed is a combination of both the horizontal and the vertical obstructions caused by the sign. Generally speaking, the area blocked from view by a given sign panel array increases as the distance from the camera to the sign increases, and decreases the higher the camera is mounted relative to the sign array. Also, the greater the lateral offset between the camera and the sign panels, the smaller the amount of blockage that will occur at a given longitudinal distance from the sign. This means that cameras located on the shoulder will be least affected by a sign if it is located over the median of the freeway, whereas a camera mounted over the freeway median would be least affected by shoulder-mounted signs.

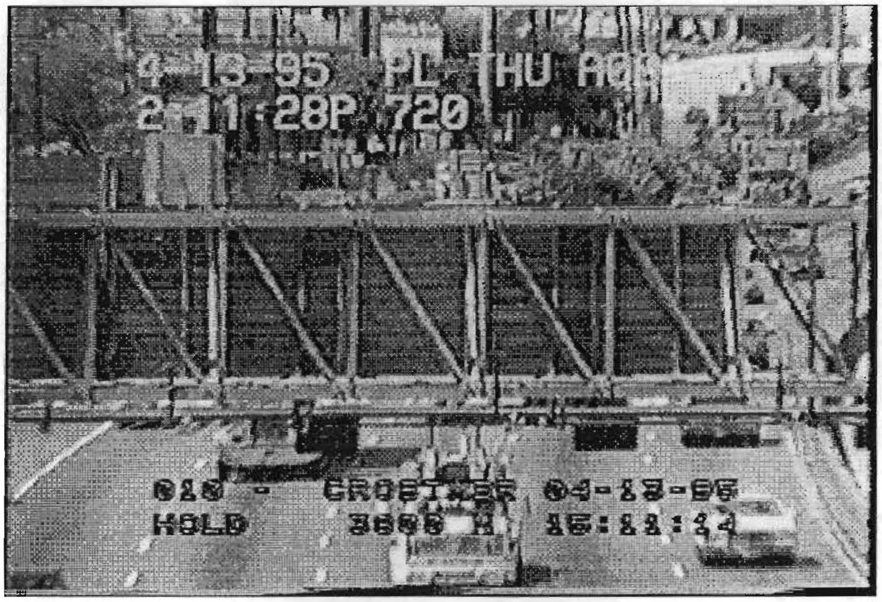


FIGURE 4. Full-Span Sign Bridge Blocking CCTV View

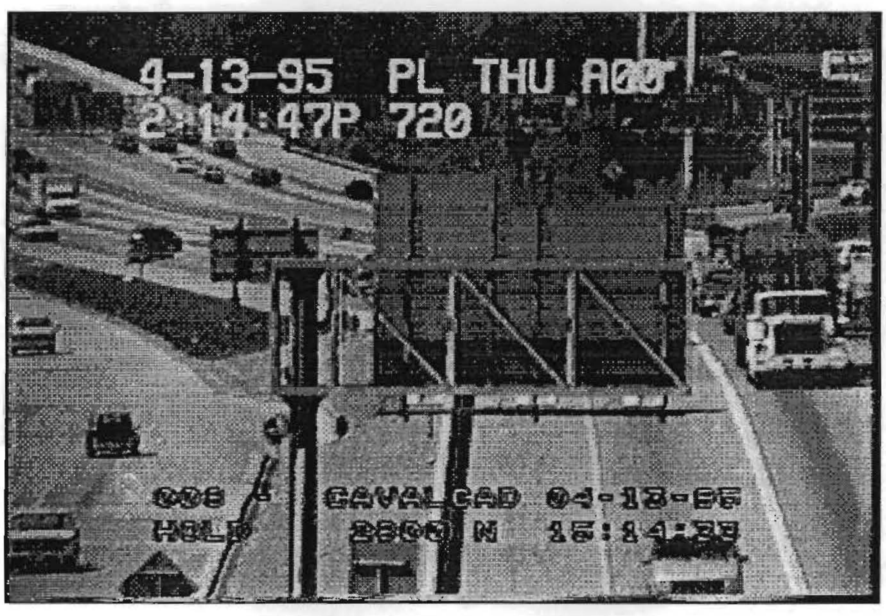


FIGURE 5. Shoulder-Mounted Signs Blocking CCTV View

It is also important to recognize that these relationships do not represent the influence of foreshortening of the visual field that occurs when viewing three-dimensional images on a two-dimensional screen. Although a sign array located further away from a CCTV camera will obscure a greater distance of freeway, the apparent blockage will seem much less because it blocks a smaller effective area of the visual field (i.e., the area on the screen that is blocked diminishes as the distance from the camera to the sign array increases).

Camera Stability

Various transportation agency personnel identified camera pole rigidity as another concern. For example, the Fort Worth District utilizes special camera support poles in 12- or 18-meter lengths, designed to exceed high-mast illumination support standards. Even with this added rigidity, some camera vibration is evident during windy conditions. The San Antonio District has opted to place cameras on the overhead sign structures. However, they have encountered difficulty at major freeway interchanges, where the structures are often attached to an elevated roadway section rather than reaching all the way to the ground. Thus, when heavy trucks use the roadway, significant camera vibration occurs due to pavement flexure.

VEHICLE DETECTOR ISSUES

Vehicle detection allows the system operator to monitor freeway traffic flow conditions in a traffic management system. For many years, transportation agencies relied almost exclusively on inductive loop detectors for these purposes. Recently, however, advances in technology have added or improved other types of detection to the list of options in a traffic management system. Various transportation agencies and equipment vendors have encountered a number of issues with respect to vehicle detection. These issues are discussed according to the type of technology employed. The technologies include:

- inductive loop detectors,
- microwave/radar traffic detectors, and
- video imaging.

Inductive Loop Detectors

Despite recent introductions of new data collection and traffic surveillance technology, inductive loop detectors remain the primary means for monitoring traffic conditions quantitatively. Because they involve saw cuts into the pavement, loop detector installation is typically included in the general contract that is let for roadway construction or reconstruction. The installation of the communications hardware, software integration, and other components necessary to actually make use of the data is then handled through a separate contract. It may be several years between the time that the loops are installed in the pavement and the time that they are hooked into the communications system and the data utilized.

Both the Fort Worth and the El Paso TxDOT Districts reported poor loop detector reliability and durability over time when the loops were installed as part of the general roadway construction contract and then not used for several years because the other components of the traffic management system were not in place. The Fort Worth District believes that loop detectors will actually have a long "shelf" life (i.e., time between installation and use in a traffic management system) if they are properly installed. They see the detector failures as being caused by poor installation practices by the contractors and have taken steps to tighten the installation specifications and inspection procedures for loops. The El Paso District, on the other hand, believes that the solution to achieving a longer-lasting loop detector is to place the wire coils within PVC conduit embedded in the pavement. They plan to try this approach on a small section of freeway in the future.

Initially, the Fort Worth District also installed a number of partial traps in between full-trap detector stations (i.e., only single detectors in each travel lane rather than dual loops spaced a given distance apart). However, they have altered this practice and now install full traps at all locations. To the Fort Worth District personnel, the small savings in installation costs are not worth the loss of accurate speed data.

Microwave/Radar Traffic Detectors

Although inductive loop detection will likely remain a staple of most freeway traffic management systems, a number of alternative detector technologies in certain applications are receiving increased attention from transportation agencies. In most cases, these technologies are non-intrusive (do not require installation within the lanes of travel) and are becoming increasingly sophisticated in their ability to obtain certain traffic parameters that may be of interest to the transportation agency.

Field experience with most of these types of technologies is somewhat limited. In depressed freeway sections, it appears that the microwave signal bounces off of the concrete walls and may limit the usefulness of these detectors in this type of freeway design. Another difficulty encountered with these technologies to date is the presence of metal guardrail fence in the median or along the shoulder of the freeway. The metal in the fence can mask the vehicle signatures read by the detectors, giving erroneous traffic flow measurements. According to the vendors, this effect can be remedied by relocating the detector and doing some fine-tuning. Nevertheless, the specification of concrete for a median barrier (a practice that is now quite common) can help reduce the potential for this type of problem.

Video Imaging

Video imaging is another emerging vehicle detection technology seeing increased usage. Generally speaking, the same types of issues raised regarding CCTV are pertinent to video imaging, since both utilize camera perspectives of freeway vehicular travel for data. However, the effects of signing and other visual occlusions tend to be less of a problem for video imaging since the camera perspective for this technology is fixed on a specific area. Also, the imaging analysis software can minimize the effects of camera vibrations.

Video imaging systems do experience operational difficulties during transition periods between daytime and nighttime lighting conditions. This is due to the longer shadows that vehicles cast. None of the experts contacted had any suggestions about how to modify freeway designs to minimize this problem. It appears that the problem, if it is to be solved, will have to be addressed primarily through improvements to the imaging software. Thus, video imaging for freeway data collection applications should still be considered experimental at this time.

RAMP METERING OPERATIONS ISSUES

Although Texas was one of the first states to experiment with entrance ramp metering back in the 1960s, ramp metering within the state has been essentially nonexistent in recent years due to funding limitations for operations and maintenance, public pressures, etc. In other states, though, ramp metering has been an effective component of several freeway management systems. Consequently, officials in many of the major urban areas statewide are once again considering the implementation of ramp metering on portions of their freeway systems.

The implementation of a ramp metering system obviously impacts the design of the entrance and exit ramps along the freeway. Experiences of other transportation agencies have yielded insights into some of the major issues that must be addressed with respect to ramp design in order for the metering system to operate effectively. These issues relate to the following:

- ramp location,
- ramp cross-section, and
- ramp length.

The following paragraphs describe the ramp metering issues relating to these design features.

Ramp Location

Ramp metering systems have an impact upon several freeway design elements. For instance, the location of the ramp entrance relative to the upstream frontage road-cross street intersection can limit the flexibility of ramp metering systems (i.e., allowable timing plans) if not enough storage capacity can be provided on the ramp proper and the section of frontage road (if it exists) between the ramp and the upstream intersection. Thus, from a ramp metering perspective, entrances located a considerable distance downstream of the frontage road intersection are preferred. One way to increase the distance between an upstream frontage road and an entrance ramp is to employ an X-shaped ramp design at cross-street arterial interchanges.

Ramp Cross-Section

Transportation agency personnel also raised the issue of the cross-section design of the ramp subbase and base. Ramp metering systems often include the provision of HOV bypass lanes. Also, some systems employ dual ramp lanes to allow two vehicles at a time to enter the freeway. Officials in Ontario, Canada, stated that they include these possibilities when designing the earthwork that will be required for ramp installation. They may in fact initially install pavement for a single ramp lane onto the base constructed for two lanes, but then are prepared to make changes to the ramp if needed in the future.

Another consideration that affects the ramp cross-section is the need to provide a police enforcement area for ramp metering violations. For instance, the California Department of Transportation provides space downstream of the ramp meter, near the end of the auxiliary acceleration lane. This creates a visual deterrent to ramp meter noncompliance while at the same time offering enforcement personnel easy access to the freeway mainlanes.

Ramp Length

The potential implementation of ramp metering also affects the length of ramp and the acceleration lane that will eventually be required on the freeway. Provisions must be made to allow vehicles at a stop on the ramp to accelerate up to merging speeds prior to joining the freeway mainlanes. The AASHTO Green Book states that nearly 490 meters will be required for a vehicle at rest to reach merge speed onto a freeway with a 113 kph design speed *(2)*. Although some of this distance is accommodated by the acceleration lane on the freeway proper, it is evident that longer ramps offer greater flexibility for future implementation of metering strategies *(3)*. This implies that shallow merge angles will be preferable, since this increases the effective ramp length.

CHANGEABLE MESSAGE SIGN AND LANE CONTROL SIGNAL ISSUES

Dynamic motorist information displays offer transportation agencies an opportunity to convey real-time traffic information to motorists. With this information, motorists are better prepared for conditions they encounter, and can alter their travel decisions if they choose. From a freeway design perspective, it is important to recognize that the various visual dynamic displays available (i.e., changeable message signs, lane control signals, signing for highway advisory radio, etc.) are only one part of the entire information system provided to motorists. This system includes the visual perspective of the roadway alignment ahead as well as the various pavement markings, signs, and other traffic control devices present. The interaction between the static freeway guide signing and a dynamic motorist information display is a particularly important consideration during final freeway design.

The potential for driver information overload at a location is one of the major concerns to be addressed during final freeway design/redesign. For example, it is common practice for agencies to place changeable message signs or lane control signals on existing overhead sign structures where possible as a cost-saving measure. On those structures that already support multiple sign panels, the addition of these dynamic information displays has the potential to overload the driver.

The 3rd edition of the Federal Highway Administration's *User's Guide To Positive Guidance* (*4*) indicates that when the number of information sources competing for a driver's attention at a point reaches more than five or six, a potential information overload condition exists. Typically, the general roadway alignment with its associated pavement markings can be considered as one information source. The typical array of other traffic control devices (such as regulatory and warning signs, delineators, etc.) will count as another information source. If the sign structure is located close to an exit or entrance ramp with the associated changes in cross-section and gore area markings, another one or two information sources must be considered by the motorist. Also, various information sources inside the vehicle (vehicle's instruments, radio, cellular telephones, etc.) may compete for the driver's attention. Because of these other information sources that are typically present, transportation agencies are advised to display no more than three sign panels on a given overhead structure (*5*). Similarly, they are advised to provide adequate spacing between overhead sign structures (Fort Worth requires a minimum of 240 meters separation).

These positive guidance principles are valid regardless of the information medium used, and can be extended to include dynamic information displays as well. In other words, it is desirable to keep the combination of guide sign panels and dynamic information display components to a maximum of three at any one location. Overall, lane control signals themselves are very simple symbolic displays, and so it is believed that an entire array at one location can generally be considered as a single information source. However, this is not the case for more complicated messages on changeable message signs. In many instances, the information to be presented to motorists requires two panels displayed in sequence, such as illustrated in Figure 6. This is equivalent to two guide sign panels, indicating that the sign structure should hold no more than one additional static guide sign.

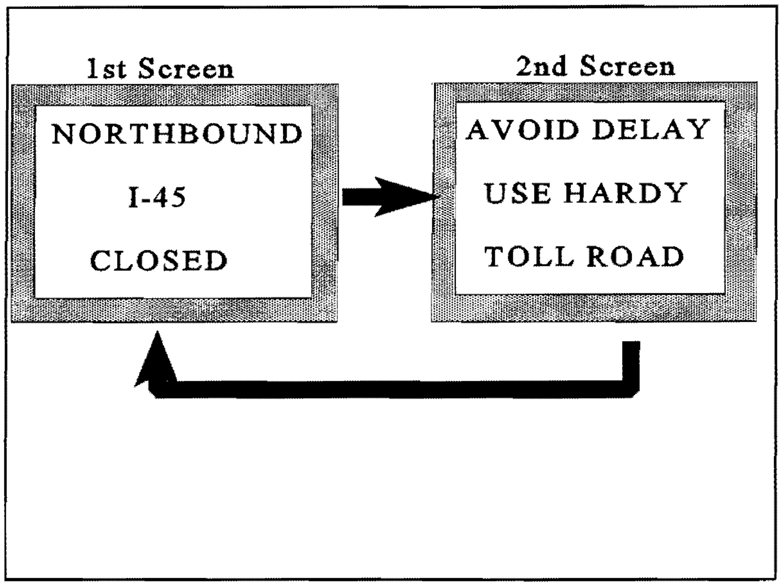


FIGURE 6. Example of a Multi-Screen Message

INCIDENT RESPONSE AND MANAGEMENT ISSUES

Incidents are a major concern to many transportation agencies. Quick and effective response to an incident has been shown to be particularly critical to urban freeway traffic operations in order to reduce both the operational impacts of the incident (i.e., motorist delay, stops, fuel consumption, vehicle emissions) and the safety impacts, such as secondary accidents caused by non-recurrent congestion (*6*). In the same manner, experience and research have shown that these impacts can be lessened by implementing various management strategies within and upstream of the incident site to increase the traffic flow capacity around the incident location, to warn drivers of downstream congestion, and to recommend that drivers utilize alternative routes around the incident.

Reducing the total duration of the incident lessens both the adverse safety and operational impacts. This total duration is compressed by reducing one or more of the four basic phases of an incident:

- incident detection time,
- incident evaluation time (to determine response needs),
- travel time of response vehicles to the incident site, and

- incident removal time.

Freeway surveillance and control systems, including components such as loop detectors and CCTV cameras, provide transportation agencies a means of significantly reducing incident detection and evaluation times. Consequently, the issues discussed previously relating to those components can be thought of as also influencing freeway incident management. However, this research effort has identified additional issues and concerns relating to incident response and management. Generally speaking, these issues affect response vehicle travel time and access to the incident site and/or incident removal times, and influence the following freeway design concerns:

- ramp spacing and emergency vehicle access,
- accident investigation sites, and
- incident response vehicle and equipment staging areas.

Ramp Spacing and Emergency Vehicle Access

It has become apparent in recent years that closely-spaced entrance and exit ramps on urban freeways can have a deleterious effect upon freeway operations. Such a design promotes freeway use for very short trips (i.e., to skip signalized intersections along the frontage road), increases vehicle weaving, and causes other operational problems. The AASHTO Green Book recommends a minimum of 1.6 kilometers between interchanges so that proper ramp lengths can be accommodated (*2*). However, many transportation agencies have adopted even greater spacings as a freeway demand control measure. For example, the number of entrances provided onto a freeway heading into or out of a central business district may be limited in order to force motorists to utilize the adjacent frontage road or other nearby arterials for a greater distance.

This design approach, while proving quite effective in reducing spot bottlenecks and other peak period operational difficulties, does pose an interesting dilemma to those responsible for responding to freeway incidents. Specifically, this approach to ramp design reduces the number of opportunities available for response vehicles to access the freeway during incident conditions. Those ramps that are available are, on average, located a farther distance away from the actual incident. This means that response vehicles must travel a farther distance through typically congested freeway conditions to reach the incident. In addition, the opportunities provided to response personnel to manage traffic around the incident (i.e., diverting freeway traffic onto nearby arterials) are also reduced.

Therefore, a trade-off exists between the advantages of less frequent ramp spacing for normal traffic flow conditions and the disadvantages of a less flexible freeway design for accommodating response needs and traffic flows during incident conditions. Furthermore, this trade-off depends upon such things as incident frequency, incident duration, and normal traffic demands, as well as what other technology is made available to facilitate incident response and management on the freeway. For example, the Houston District of TxDOT has installed motorized barrier gates in the median concrete barrier at several freeway locations within its jurisdiction. These gates can be opened during incident conditions to allow emergency vehicles access to an incident site from the opposite side of the freeway. Also, these gates can allow response personnel to clear out traffic that is blocked upstream of an incident as well.

Accident Investigation Sites

Accident investigation sites (AIS) are low-cost specially designated and signed areas off the freeway where damaged vehicles can be moved, motorists can exchange information, and police and motorists can complete necessary accident forms (*6*). These areas are located out of view of other freeway motorists, thereby reducing the influence of driver "rubbernecking" and the congestion it causes. Although benefit-cost analyses have shown AIS to be very cost-effective when used, utilization rates within Texas are fairly low. In general, it appears that extensive promotion campaigns of some type are required in order to motivate motorists and police officers to use the AIS.

The major freeway design issues that pertain to the installation and operation of AIS are the selection of actual AIS locations along the freeway, the decision of where within the freeway right-of-way to place the AIS at each location (or even whether it should be placed within the right-of-way), and the specific design elements of the AIS themselves. Traditionally, AIS have been placed at high-accident locations. However, accident histories may change markedly once a freeway undergoes major reconstruction. Furthermore, the AIS locations in the past were often selected based on where they could be retrofitted into existing freeway geometrics. Therefore, AIS placement decisions as part of a freeway reconstruction should emphasize ease of accessibility so that there is no disincentive for motorists and/or police to utilize them. Also, establishing frequent placement of AIS throughout the freeway system may foster greater motorist and police awareness of the presence of AIS and eventual acceptance. Unfortunately, data are currently not available upon which to judge the most cost-effective spacing of AIS as a function of freeway characteristics. However, it is apparent that all proposed AIS locations should be discussed with local law enforcement officials before final placement decisions are made. A latter section of this report provides specific guidelines relating to the design of AIS.

Incident Response Vehicle and Equipment Staging Areas

Another incident management strategy identified that has freeway design implications is the provision of special staging areas at selected points along the freeway where certain types of equipment and materials (such as sand to spread over truck spills, special traffic control devices for management of major incidents, etc.) can be stored and where vehicles and personnel can coordinate response activities. These areas can help facilitate incident response actions and lead to a shorter total incident duration. Los Angeles has had incident equipment storage and staging areas in place throughout their freeway system for several years (*7*). Several other jurisdictions nationwide have, or are in the process of implementing, similar staging areas for major incident response and management.

Data from Houston indicate that major freeway incidents are three to four times more likely to occur within freeway-to-freeway interchanges than between them (*8*), which suggests that staging areas should be located at or near such interchanges. Fortunately, most freeway interchange designs have space available within the interchange right-of-way itself to establish a special staging area. However, the data are not yet available to indicate whether each and every interchange should have a staging area, or whether only those serving more than some total daily volume should be provided. If such areas are included in the redesign, access to and from the site must be considered, and design criteria for larger trucks (i.e., curb radii, median openings, etc.) must be used to allow access by specialized response equipment. Additional research and analysis of this question is needed.

3. FREEWAY DESIGN GUIDELINES FOR TRAFFIC MANAGEMENT SYSTEM COMPONENTS

As stated previously, freeway construction and reconstruction offers an excellent opportunity for transportation agencies to incorporate traffic management system components into freeway design decisions. In general, synergism between final freeway design and traffic management system components is maximized if the traffic management system design itself occurs simultaneously or even in advance of the final design stage for general reconstruction. However, even if this is not possible, there are several items that can be incorporated into the freeway redesign to facilitate future system component implementation. The sections that follow outline some of the more critical traffic management system considerations that should be addressed in final freeway design or redesign.

GUIDELINES FOR SURVEILLANCE AND CONTROL COMMUNICATIONS TRUNK LINES

Based on past experiences of several transportation agencies, provisions for a communications trunk line should be included in urban freeway reconstruction design plans if a computerized traffic management system is to be implemented within the reconstructed section at any point within a 10-year time frame. Key decisions that need to be made as part of the freeway redesign process include 1) where the trunk line will be placed within the reconstructed freeway cross-section, and 2) which type of trunk line protection that will be used.

Trunk Line Placement

In general, a data communications trunk line for traffic management purposes should be located in one of two places within the freeway right-of-way:

- The separation between the freeway travel lanes and the adjacent frontage road, or
- The median of the freeway.

Figure 7 illustrates the options for data communications trunk line placement. Locating the trunk line within the freeway median allows equal access to the line for traffic management components on both sides of the freeway. Of course, this approach is appropriate only if the various components themselves offer direct connections to the median. For example, variable message signs and closed-circuit television cameras can be mounted on overhead sign bridges that are supported in the median, and these can be easily connected to the trunk line by running the cable up the structure and over to the sign or camera. Unfortunately, any components that are located on the right side of the roadway (such as ramp metering controllers) will require buried conduits to cross under the freeway mainlanes, which tends to negate any other benefits that might be achieved by a median trunk line location. Thus, a median trunk line is not appropriate if the components are only accessible from the outer shoulders of the freeway.

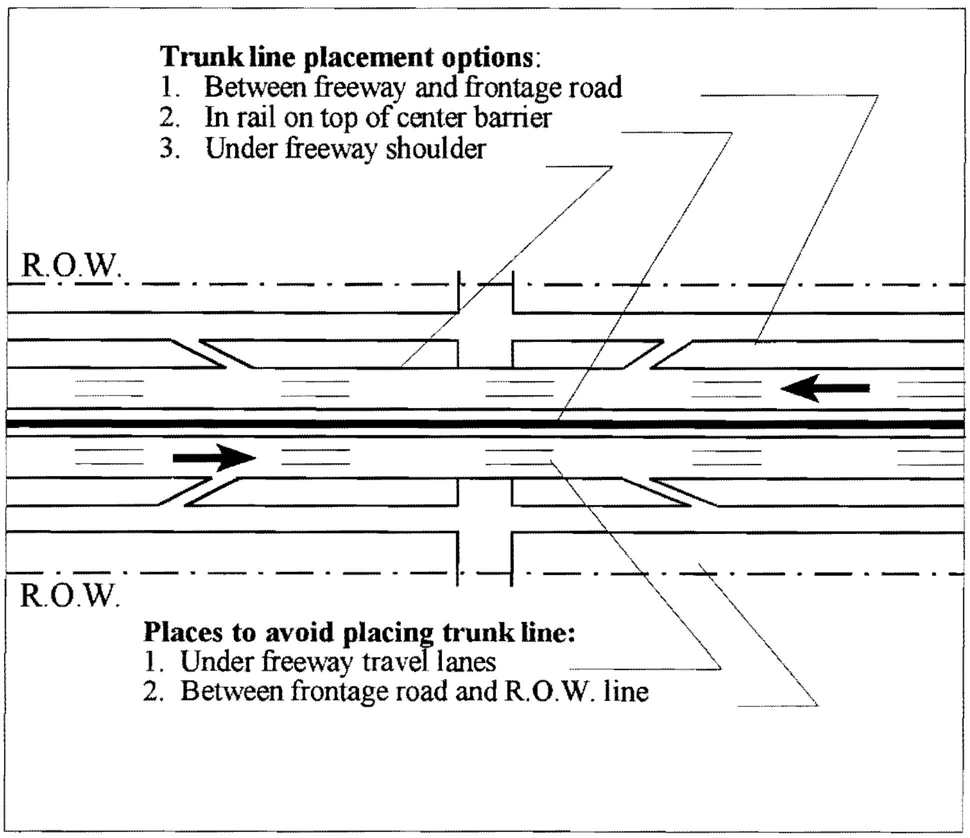


FIGURE 7. Placement Options for Data Communications Trunk Lines

Currently, the more common placement practice is to bury the trunk line within the separation between the freeway and the frontage road. In some instances, the trunk line can be located under the freeway shoulder. However, because of the potential for severe traffic disruptions in the event of a trunk line break or other maintenance need, the trunk line should not be placed directly underneath the freeway mainlanes if at all possible. The trunk line **should not** be buried in the outer separation between the frontage road and the edge of the right-of-way, as this location subjects the line to inadvertent breaks and cuts by adjacent land owners during driveway construction or other activities.

Trunk Line Protection

Direct Burial Cable

Transportation agencies have the option of using direct burial cable or of pulling the cable through metal or plastic conduit when developing a communications trunk line along the freeway (above-ground, pole-mounted trunk lines are not typically used for freeway systems in Texas). It is common practice in Texas to install a PVC conduit system as part of the regular roadway construction contract so that a separate traffic management system contractor with more understanding and experience with the installation of these systems (but not necessarily with the heavy construction equipment needed to bury conduit and cable) can come in later and run the actual cabling. If this approach is followed, inspection of hardware details (i.e., proper grounding of junction boxes, adequate seals against moisture, proper top plate thicknesses, etc.) must be stressed during construction to avoid problems in this equipment that will not be detected otherwise until it is time to install the cable and other components of the system. This can be particularly important if the design calls for the conduit to be encased in concrete to protect it from accidental breakage due to utility work or other maintenance efforts.

In some instances, staged implementation of a system may require that multiple cables be placed within the same conduit but installed at different times. If this is anticipated, separate conduits should be installed for each cable that is anticipated, and if possible, an extra conduit placed for future use. This eliminates the snagging and other problems caused when trying to pull another cable through conduit where one already exists. This process is facilitated by the use of a large outer conduit that contains several smaller innerducts, as Figure 8 depicts.

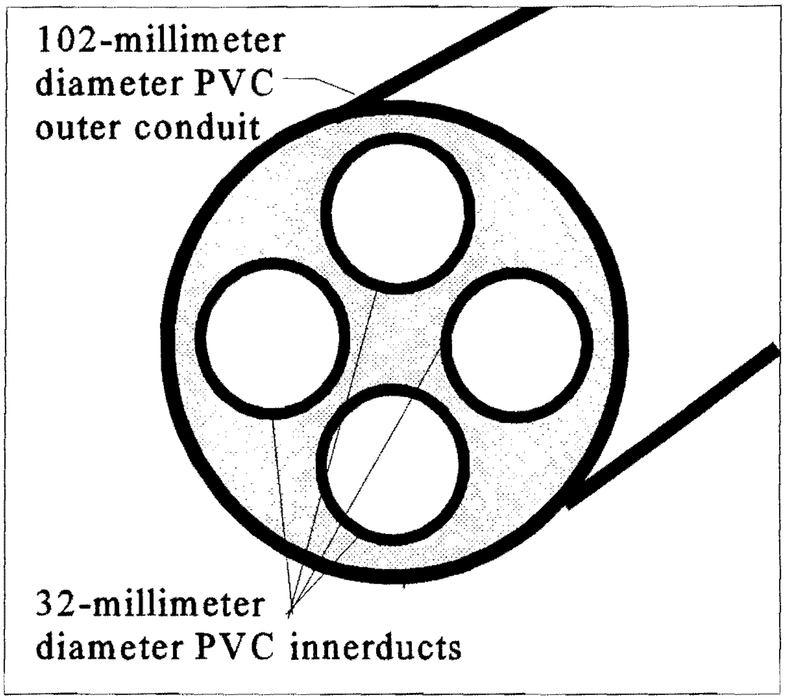


FIGURE 8. Cross-Section of Innerduct Conduit

When buried conduits are used to protect the communications trunk line, the allowable distance between pull-boxes depends on the type of cable used. Coaxial and twisted-pair lines generally require pull-boxes every 91 meters. However, fiberoptic cable, now being used by many agencies, allows for much longer runs between boxes. Specifically, fiberoptic cable can easily accommodate 400-meter runs between pull-boxes (*9*).

Acceptable bend radii for conduit are a function of the diameter of fiberoptic cable being used. For a 102-millimeter conduit, experience indicates that sweeping elbow connectors with radii of between 610 and 910 millimeters work adequately.

The location of buried conduit should be adequately marked to reduce the potential of accidental breakage due to trenching or digging for utilities, roadway maintenance, etc. The Fort Worth District places warning signs above ground over its conduit, and also marks the conduit's location with a metalized mylar tape placed in the ground 0.3 meters above the conduit. The agency's name, contact telephone number, and a fiberoptic cable warning are imprinted on the tape.

Median Barrier Rail

If the trunk is installed in the freeway median, another alternative is to place the trunk line in a metal tray or rail mounted on top of the median concrete traffic barrier. This above-ground alternative is cheaper to construct than buried conduit and is easier to maintain. However, some breaks will likely occur in the line when the traffic barrier sustains major damage (such as impacts by large semi-tractor trailers). Consequently, redundancy in the trunk line network is even more of a critical concern when it is mounted on top of a barrier (consult the *Communications Handbook for Traffic Control Systems* for additional information concerning trunk line redundancy and other design issues [*9*]). Also, care must be taken to ensure that the barrier rail is not susceptible to vandalism and that aesthetics of the freeway are not compromised by the introduction of the rail on top of the barrier.

GUIDELINES FOR INDUCTIVE LOOP DETECTORS

The most common form of traffic flow data collection on freeway facilities is by inductive loop detectors. Traffic management systems typically rely on loop detectors to determine traffic volumes, speeds, and occupancies (i.e., the amount of time the detector is actuated by vehicles in a given period of time) in real time. These data are used to establish ramp metering rates, to identify incident locations, to determine the effect of motorist information systems upon driver behavior, and to perform other activities.

Freeway operations are characterized by high-speed, high-volume flows that test the limits of loop detection data accuracy. However, these operating conditions can vary dramatically, particularly if congestion develops and queues back over the loops. Weaving maneuvers can also reduce the accuracy of the loop detectors. Therefore, an inductive loop detector system must be properly designed and installed in order to obtain the type and quality of data needed to successfully operate a freeway traffic management system.

Type of Wire

Loop detectors are created by cutting slots into the travel lane pavement in the form of a square, rectangle, or other shape and placing wire in this slot. Recent research results (*10*) indicate that the type of wire used has a dramatic effect on the accuracy and precision of a loop detector. For freeway traffic management purposes, multi-strand wire should be used instead of the single-strand wire commonly used for arterial street signal control. Multi-strand wire requires a slightly wider saw cut slot (8 millimeters rather than 6 millimeters).

Loop Detector Configuration

For freeway traffic management purposes, TxDOT districts typically use dual inductive loops spaced between 4.6 and 6.1 meters apart, leading edge to leading edge. Recent research indicates that loop spacings up to approximately 9 meters can be used without a significant reduction in the accuracy of speed data. Whatever spacing is used, full loop detector trap stations should be placed in each travel lane. This allows partial data to still be collected even if a loop or a pair of loops in a given lane fail. Furthermore, the Fort Worth District has found that single (also called partial) loop detector configurations in a given lane that obtain volume data only have not proven to be particularly useful.

Loop Detector Placement

Freeway traffic management systems typically rely on loop detectors spaced approximately every 0.8 kilometers. The cost-effectiveness of this spacing has been verified through research results as well (*11*). However, it is important to ensure that loop detectors are installed where data needs are the greatest and will provide the type of data desired. Generally speaking, loop detectors placed within the influence areas of weaving sections or ramp junctions (generally 450 meters upstream of the section or junction) will not provide the same indication of traffic conditions (particularly speeds and the distribution of traffic over available lanes) as loops placed away from these influence areas. Furthermore, it may not be possible to accurately measure speeds within weaving sections because of the intense lane-changing activity that typically occurs in these sections.

Detector Units

Research has also shown that in order to accurately measure freeway speeds with loop detectors, identical make and model detector units (which amplify the inductance changes in the wire when a vehicle passes over the loop) need to be utilized for all loop detectors at a given location. Failure to do so can result in highly erratic speed measurements (*10*). However, the Fort Worth District has found that the use of identical detector units tend to support crosstalk between detectors. They emphasize the need to use detector units with as wide a range of available frequencies as possible in order to allow this crosstalk to be minimized.

GUIDELINES FOR CLOSED-CIRCUIT TELEVISION (CCTV) INSTALLATIONS

The eventual implementation of closed-circuit television (CCTV), whether as a traffic monitoring and incident verification tool or for video imaging purposes, interacts significantly with both preliminary and final freeway design decisions. Commonly, it is desirable to have CCTV line-of-sight capabilities for distances at least 0.8 kilometers in both directions of travel. Furthermore, it is advantageous to be able to view conditions along the adjacent frontage roads (where they exist), because traffic conditions along them can influence ramp operations and ultimately freeway flow characteristics. Also, because of these long viewing distances, camera stability is also important to the effective utilization of CCTV in a traffic management system.

Fitting CCTV cameras into an existing freeway environment is more difficult than fitting them onto a new freeway facility. Assorted geometric features, traffic control devices, and adjacent roadside development can cause visual obstructions. Roadside development can be particularly troublesome because it can occur years after the selection and installation of camera locations. In addition, other freeway design practices unrelated to the provision for, and use of, CCTV can cause geometric obstructions. For these reasons, it is sometimes difficult to find CCTV mounting locations that offer good visibility over the camera's entire operating range. Fortunately, some of these problems can be reduced if CCTV placement occurs at the same time, or even slightly before, final freeway design.

From a visual perspective, depressed freeway sections tend to provide the best viewing conditions for CCTV. This is because the height differential is greater between the cameras and the various freeway obstruction (guide sign structures, cross-street overpasses, etc.). Another advantage is that the frontage road intersections of a diamond interchange are elevated, making it easier to locate a single camera where both intersections of an interchange can be monitored. Finally, depressed freeways do not rise and fall in order to pass over cross-street diamond interchanges and are less likely to generate a "roller-coaster" freeway alignment perspective that tends to hide sections of the freeway travel lanes from CCTV view.

Camera Mounting Considerations

CCTV cameras should be mounted as high as practical to provide the greatest viewing distance and to minimize the number of obstructions caused by overpasses, sign structures, etc. For this reason, it is advantageous to mount cameras on fill sections within the freeway right-of-way (such as at frontage road intersections where the cross-street passes over the freeway) in order to increase the effective height of the camera above the freeway. However, care must be taken to ensure that adequate support is available in the fill material to provide a stable camera mount. The Fort Worth District uses a drilled shaft for camera pole foundations in these situations.

On elevated freeway sections, cameras should not be mounted on overhead sign structures that are attached to the freeway deck; rather, the structure itself should have supports that reach all the way to the ground. In all cases, camera mounts must be extremely solid so as to minimize vibration and provide a stable picture to system operators. Generally speaking, luminaries or other pole supports greater than 12 meters high do not tend to be stable enough to use as a camera mount.

Camera Location

The selection of CCTV camera locations along a section of freeway cannot be constrained to a simple step-by-step process. Many factors can affect camera placement and must be considered using basic engineering judgement. However, the following paragraphs provide guidance regarding some of the factors that should be considered.

Fixed Objects

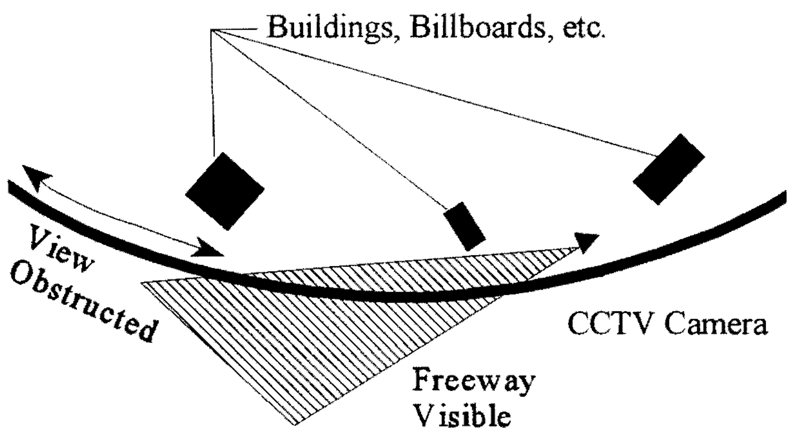
Cross-street bridges, pedestrian overpasses, HOV and braided ramp designs, and freeway-to-freeway interchanges represent major obstacles to CCTV visibility. Attempts should be made to locate cameras so that these obstructions fall midway between sequential cameras. At diamond interchanges where the freeway passes over the cross-street arterial, cameras would thus be positioned between the interchanges and would then allow frontage road/cross-street intersections as well as freeway operations to be monitored. In this situation, it may be beneficial to alternate cameras from one side of the freeway to the other so that both cross-street frontage road intersections at each interchange can be monitored in addition to the freeway mainlanes. As an alternative, it may be necessary to place cameras closer together in the vicinity of fixed objects instead of continuing the spacing used elsewhere along the freeway.

Horizontal Curves

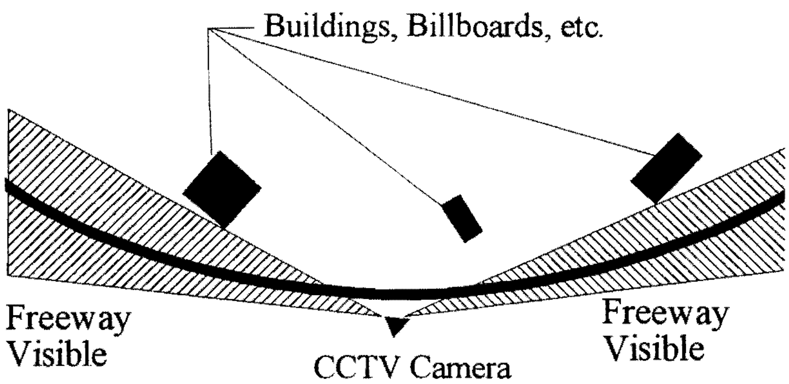
Horizontal curves can create blind spots when billboards or large buildings are constructed close to the freeway right-of-way line (see Figure 9a). These objects can be constructed even after the cameras have been installed. Obviously, the greater the length of curve and the degree of curvature, the greater the potential for roadside obstructions. This potential can be minimized by locating the camera on the outer edge of the curve (see Figure 9b). Although poor camera location choices can often be eliminated through a review of plan sheets, all potential locations should be verified by actual site inspections using a bucket truck and camera prior to final location selection. Future advances in computer graphics and solid modeling software applications will further aid the designer in identifying these locations.

Overhead Guide Signs

Sign structures are perhaps the most difficult aspect of final freeway design that must be accommodated in CCTV placement decisions. On one hand, driver information processing guidelines state that guide signs should be spread along the length of freeway so as to not overload or underload the driver. For high information areas, full-span overhead sign structures are recommended to facilitate information processing. Conversely, the effectiveness of CCTV monitoring is enhanced if fewer obstructions (such as signs and sign structures) are located in the visual field.



(a) CCTV View Obstructed



(b) Improved CCTV Viewing Potential

FIGURE 9. Effect of Horizontal Alignment on CCTV Viewing Range

The effect of freeway guide signs upon CCTV visibility is minimized if the height differential between the camera and the sign or sign structure is as great as possible. Also, increasing the lateral offset between cameras and signs reduces the obstruction potential of the sign. This means that cameras mounted between the freeway and the frontage road will be less affected by guide signs mounted from, and displayed over, the freeway median. Likewise, signs and sign structures located on the right side of the freeway will have less of an effect upon CCTV visibility if the camera is mounted on or near the median of the freeway.

Longitudinally, cameras located immediately adjacent to a guide sign structure are obstructed very little by the guide signs. However, as the distance from the sign structure to the camera increases, the length of freeway that becomes obstructed from view increases proportionally. Although guide sign locations are in large part dictated by the MUTCD, designers of the signing system should remain cognizant of how the sign structures will affect CCTV visibility. Conversely, traffic management system designers should be aware of the visibility limitations that sign bridges create, and recognize the possibility that additional cameras placed closer together may be required to adequately monitor traffic conditions in areas where extensive guide signing is present.

Frontage Road Intersections

CCTV should be placed a minimum of 15 meters away from the corner of frontage road/cross-street intersections. This keeps the pan and tilt limitations of the CCTV hardware from creating "blind spots" within the intersection. Also, placement of the CCTV on a fill section with retaining wall (such as at the frontage road intersections on depressed freeways) necessitates an adequate base for the camera pole be installed in the fill section at the time of construction, because it is very difficult to retrofit such a support into an existing fill section.

Maintenance Access

Maintenance access is a final concern regarding CCTV location. Care is required to locate CCTV cameras so that maintenance personnel can access them as required. It may be necessary to specify a special concrete or gravel pad adjacent to the mounting location of a CCTV camera to provide a stable base for the bucket truck outriggers that will be needed. If the camera is intended to be accessed by the maintenance vehicle while on the shoulder, enough lateral clearance should be provided so that the outriggers can be put down without impinging upon the freeway travel lanes and necessitating a lane closure.

GUIDELINES FOR CHANGEABLE MESSAGE SIGN AND LANE CONTROL SIGNAL INSTALLATIONS

Other important traffic management components that have implication in final freeway design are the visual motorist information displays, i.e., changeable message signs and lane control signals. Care must be taken to ensure that the placement of these displays allows adequate viewing time, provides information that is consistent and unambiguous to that implied by the freeway geometrics, and does not underload or overload driver information processing capabilities when combined with the other information sources present along the freeway. CMSs must also be placed far enough in advance of exits to provide motorists with adequate time for lane changes if necessary (to divert upstream of an accident, for example). Consequently, display placement must be coordinated with the following freeway design features:

- fixed objects (ramps, cross-streets, pedestrian overpasses),
- horizontal and vertical curves, and
- freeway guide signs.

Fixed Objects

The location of changeable message signs and lane control signals must be established in coordination with fixed object locations such as pedestrian overpasses, cross-street bridges, concrete abutments, etc. Sight distance limitations caused by horizontal and vertical curvature must also be taken into consideration. Just as for static freeway guide signing, dynamic information displays must be visible from far enough away for a motorist to detect, read, and correctly interpret the message being presented. Generally speaking, a freeway designer cannot easily relocate fixed objects once they have been set, and roadway planning has moved forward; hence, coordination between these design elements and the desired position of the motorist information displays is very important.

Current guidelines specify six seconds viewing time as the absolute minimum for a typical three-line changeable message sign (*12*). This is a travel distance of approximately 160 meters at normal freeway speeds. Even longer viewing times may be necessary. The Fort Worth District, for example, requires a visibility distance of 300 meters for CMSs. Efforts should always be made to provide more than the minimum viewing time to motorists.

Horizontal and Vertical Curves

Plan and profile drawings of the freeway alignment can be used to estimate available sight distance to proposed changeable message sign locations. These estimates should be verified through actual site inspections if the freeway alignment is not being completely reconstructed. Also, it is important to consider the sign's mounting position when determining the necessary sight distance. Specifically, side-mounted signs can require visibility distances greater than that required simply by the minimum exposure time for the message. This is because a driver needs to be able to finish reading the message on a side-mounted sign by the time the angle between the driver and the sign exceeds 10 degrees (*12*). In contrast, drivers can generally read changeable message signs mounted on overhead sign structures until they are approximately 15 meters from the sign.

Lane control signals suffer from the parallax problem that plagues lane assignment arrows on static guide signs and so should not be mounted on horizontal curves if possible. Because they use simple symbols and colors to communicate with drivers, reading times for lane control signals are much shorter than for multi-line changeable message signs. However, they are also much smaller and thus more difficult to detect in a complex visual driving environment. In addition, large trucks can easily obscure them in high volume traffic conditions. Consequently, sight distances equivalent to those for changeable message signs are recommended for lane control signals as well.

Freeway Guide Signs

Care must be taken during final freeway design to coordinate the development of the overall information system along the freeway, including the dynamic message components. It is often tempting to combine a changeable message sign and/or lane control signals with static guide signs on a given overhead sign structure. However, no more than one static guide sign panel should be displayed in conjunction with a changeable message sign on a given structure to avoid information overload at that point. For the same reason, lane control signals should not be placed on overhead sign structures that will have more than two guide sign panels installed on them.

GUIDELINES FOR INCIDENT RESPONSE AND MANAGEMENT

Incident response and management needs should be a consideration throughout the freeway design process. The ability to facilitate emergency vehicle travel time and access to an incident location can dramatically affect congestion levels in a freeway corridor, particularly in peak travel periods. Also, the ability to quickly remove an incident from the freeway can significantly improve traffic conditions within the freeway corridor. Accident investigation sites and median barrier gates are two freeway design features that can aid in the quick removal of incidents from the freeway.

Accident Investigation Sites

Accident investigation sites must be easily accessible from the freeway, requiring a minimum number of turns and travel distance after leaving the freeway. The sites can be constructed in the following locations:

- on the freeway right-of-way in the separation between the freeway and frontage road or underneath a bridge structure,
- in the outer separation between the frontage road and the right-of-way line,
- on existing parking facilities on property abutting the freeway right-of-way, or
- in public curb parking spaces on local streets or frontage roads near the freeway.

If accident investigation sites are to be included in a freeway reconstruction project, it will be beneficial if an entire system of sites can be installed. Incomplete systems make it difficult for drivers to remember that accident investigation sites are available, to know whether or not a site is available in a particular area, and where such sites are located.

An accident investigation site should have space for parking a minimum of five vehicles. This equates to a minimum size of 92 square meters. Also, there should be a minimum of 31 meters longitudinally to pull into and out of curb parking accident investigation sites.

Additional guidelines are available in the report *Promotional Issues Related to Off-Site Accident Investigation (6)*.

Median Barrier Gates

Another freeway design feature that facilitates incident response and management is the provision of access gates periodically in the concrete median barrier. These gates allow emergency vehicles to gain access to an incident site from the opposite direction of travel. In addition, they can allow freeway traffic trapped upstream of an incident to be cleared. Since they remain closed when traffic conditions are normal, there is no break in the barrier where drivers might try to make an illegal u-turn or strike an exposed barrier end.

In the past, some agencies have expressed concern over the crash worthiness of these types of gates. However, at least one manufacturer has developed a motorized gate that passes concrete barrier crash tests. These gates have successfully been installed at several locations in Houston. The gate can be operated from the site or remotely from a traffic management center. In the event of power loss, the gate can be cranked opened manually. The gate is anchored to a concrete pad at least 203 millimeters thick.

4. SUMMARY

This report documents a number of freeway design issues that have affected the efforts of TxDOT and other transportation agencies to install and operate various traffic management system components. In addition, the report describes various design features of the system components themselves that have affected how effectively the components operate in an overall traffic management system. These issues are then consolidated into a set of design guidelines that engineers should consider during the final freeway design phase as well as during the traffic management system design itself.

On the pages that follow, the guidelines have been condensed into a tabular format. The guidelines are subdivided into a general freeway design feature category, and then by categories corresponding to specific traffic management components.

TABLE 1. Summary of Freeway and Traffic Management Design Concerns Affecting Operations

Category	Considerations
	Freeway Design Features
Entrance ramps	Entrance ramps should be as long as possible to allow for future implementation of ramp metering systems. The ramps should be located far downstream from signalized intersections so that any queuing on the ramp and frontage road (if ramp metering is implemented in the future) does not affect the operations of that signal.
Roadway alignment	"Roller-coaster" freeway alignments that pass over cross-street arterials and then return to grade can create visibility problems for future CCTV installations and should be avoided.
	Data Communications Trunk Line
Ground-box spacing	Ground boxes for data communications trunk lines can be up to 460 meters apart when using fiberoptic data communications lines. In contrast, coaxial or twisted-pair communications lines require pull boxes every 90 meters or less.
Buried conduit-size	Buried conduits should have the potential for future expansion. This expansion can be facilitated by the provision of innerducts in a larger outer conduit (one or more innerducts which are left unused in the initial installation).
Buried conduit-bend radii	Bends in buried conduit should be handled with sweeping elbows with radii 8 to 10 times the diameter of the conduit.

TABLE 1. (Continued)

Category	Considerations
Buried conduit-freeway locations	Data communications trunk lines can be buried between the freeway and frontage road or under the outer shoulder of the freeway. Buried conduit locations should be clearly marked above ground with warning signs and below ground with continuous warning tape located 0.3 meters above the conduit itself. Data communications trunk lines should **NOT** be buried between the frontage road and the edge of right-of-way. Data communications trunk lines should **NOT** be buried longitudinally under the mainlanes of the freeway.
Buried conduit-frontage road locations	Trunk lines should not be buried near the corners of any frontage road intersections. Additions of right or left-turn lanes, new signal hardware, etc. can increase the chance of inadvertent breaks. Buried conduits should be included across all four approaches at frontage road intersections when they are reconstructed, even if no data communications lines are presently needed. If conduits are already anticipated, they should be large enough to provide spare capacity if future data communications upgrades and/or expansion occur.
Concrete barrier rails	Barrier rails placed on the concrete median barrier for the data communications trunk line should be used only if the majority of the electronic traffic management components can tie into the trunk line without requiring lateral buried conduit runs from the outer edge of the freeway to the median.
Inductive Loop Detectors	
Wire type	Loop detectors should use multi-strand polyethylene insulated #18-#22 cable.

TABLE 1. (Continued)

Category	Considerations
Configuration	Loop detectors are cost-effective at spacings as close as 0.8 kilometers. Speed measurements are reasonably accurate when the length of the speed trap is up to 9 meters. Common TxDOT practice is to space loops 4.6 to 6.1 meters apart, leading edge to leading edge.
Detector amplifier units	The detector amplifier units for a given loop detector trap station must be of the same make and model. The detector unit should also have as large an available frequency range as possible to avoid problems with crosstalk between detectors.
	Closed-Circuit Television (CCTV)
Camera mounts	CCTV should be mounted on supports that reach all the way to the ground rather than on supports connected only to elevated freeway decks or ramp connections. The differential between guide sign and CCTV mounting heights should be as great as possible to reduce the obstruction potential of the signs on CCTV viewing.
Camera location	Cameras may need to be alternated on both sides of the freeway to allow full view of the freeway and frontage road near fixed obstructions such as cross-street overpasses and underpasses, T-ramps, pedestrian bridges, etc. Cameras may need to be placed closer together near fixed objects to provide adequate freeway visibility. It is desirable to locate cameras near the middle (outer edge) of horizontal curves to avoid future view blockages by roadside development.

TABLE 1. (Continued)

Category	Considerations
Guide sign interactions	Guide sign sequences should be designed with CCTV in mind. It is advantageous to locate large guide sign structures immediately adjacent to anticipated CCTV locations or approximately midpoint between anticipated camera locations.
Changeable Message Signs/Lane Control Signals	
Mounting locations	To avoid parallax problems, LCS should not be mounted on horizontal curves if possible. CMSs should have sight distance equivalent to a minimum of six seconds of available viewing time by approaching motorists.
Guide sign interactions	No more than one additional guide sign should be mounted on an overhead sign structure with a CMS. LCS should not be mounted on sign structures supporting more than two guide sign panels.

5. REFERENCES

1. L.K. Lee, M. Zachariah, and P. Everett. CCTV Camera Site Selection: A Field Experience. *Proceedings*, ITS America Annual Meeting, Washington, D.C. March 1995, pp. 441-446.

2. *A Policy on Geometric Design of Highways and Streets*. American Association of State Highway and Transportation Officials, Washington, D.C. 1990.

3. S. Sharma and C.J. Messer. *Distance Requirements for Ramp Metering*. Report No. FHWA/TX-95/1392-5. Texas Transportation Institute, College Station, Texas. November 1994.

4. H. Lunenfeld and G.J. Alexander. *A Users' Guide to Positive Guidance.* Report No. FHWA-SA-90-017. FHWA, U.S. Department of Transportation, Washington, D.C. September 1990.

5. *Revision 1 to the Texas Highway Operations Manual.* Report No. FHWA/TX-94/1232-3, Revision 1. Texas Transportation Institute, College Station, Texas. September 1994.

6. C.L. Dudek, W.R. McCasland, and E.N. Burns. *Promotional Issues Related to Off-Site Accident Investigation.* Report No. FHWA/RD-87/036. FHWA, U.S. Department of Transportation, Washington, D.C. July 1987.

7. C.L. Dudek and G.L. Ullman. *Freeway Corridor Management.* NCHRP Synthesis of Highway Practice No.177. TRB, National Research Council, Washington, D.C. March 1992.

8. M.A. Ogden, J.M. Mounce, D.R. Middleton, and G.L. Ullman. *Traffic Management in Response to Major Freeway Incidents, Volume I.* Report No. FHWA/TX-94/1345-2F. Texas Transportation Institute, College Station, Texas. August 1994.

9. R.L. Gordon, R.A. Reiss, W.M. Dunn, and D.R. Morehead. *Communications Handbook for Traffic Control Systems.* Report No. FHWA-SA-93-052. FHWA, U.S. Department of Transportation, Washington, D.C. April 1993.

10. D.L. Woods, B.P. Cronin, and R.A. Hamm. *Speed Measurement with Inductance Loop Speed Traps.* Report No. FHWA/TX-95/1392-8. Texas Transportation Institute, College Station, Texas. August 1994.

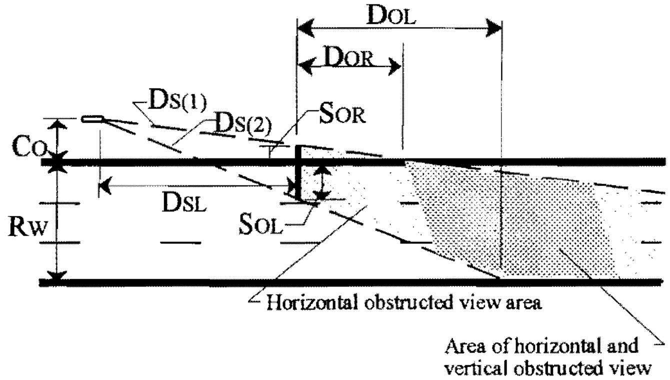
11. D.L. Woods and N.J. Rowan. *Effective Placement of Detectors for Computerized Traffic Control Summary Report.* Report No. FHWA/TX-95/1392-9F. Texas Transportation Institute, College Station, Texas. December 1994.

12. C.L. Dudek. *Guidelines on the Use and Operation of Changeable Message Signs.* Report No. FHWA/TX-92/1232-9. Texas Transportation Institute, College Station, Texas. November 1992.

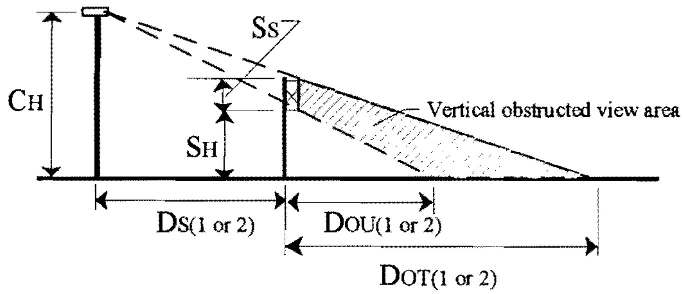
APPENDIX

EFFECT OF CAMERA AND SIGN LOCATION ON FREEWAY VISIBILITY

Top View



Side View



CO = Camera Offset (lateral)
CH = Camera Height
SOL = Sign Offset Left
SOR = Sign Offset Right
SS = Sign Size (height)
SH = Sign Height (to bottom of sign)
DOR = Distance from sign to Obstructed View on Right edge of roadway
DOL = Distance from sign to Obstructed View on Left edge of roadway
SOL = Sign Offset to Left of roadway edge
SOR = Sign Offset to Right of roadway edge
DSL = Distance from camera to Sign Longitudinally
DS(1) = Distance from camera to right edge of Sign
DS(2) = Distance from camera to left edge of Sign
DOU(1 or 2) = Distance from sign edge to beginning of Obstructed view Underneath sign
DOT(1 or 2) = Distance from sign edge to end of Obstructed view above Top of sign

Relationships:

Eqn 1: $DS(1) = ([CO - SOR]^2 + DSL^2)^{1/2}$

Eqn 2: $DS(2) = ([CO - SOL]^2 + DSL^2)^{1/2}$

Eqn 3: $DOU(I) = (CH \cdot DS(I))/(CH - SH) \quad I = 1,2$

Eqn 4: $DOT(I) = (CH \cdot DS(I))/(CH - SH - SS) \quad I = 1,2$

Eqn 5: $DOL = (SOL \cdot DSL)/(CO - SOL)$

Eqn 6: $DOR = ([RW - SOR]DSL)/(CO + SOR)$