TRANSIT COOPERATIVE RESEARCH PROGRAM

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# TCRP Report 4

# Aids for Rail Car Side-Door Observation

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TRANSIT COOPERATIVE RESEARCH PROGRAM

# Report 4

# Aids for Rail Car Side-Door Observation

**THE TELEPHONICS CORPORATION**
**Huntington, NY**

*Subject Area*

Public Transit

Research Sponsored by the Federal Transit Administration in
Cooperation with the Transit Development Corporation

**TRANSPORTATION RESEARCH BOARD**
**NATIONAL RESEARCH COUNCIL**

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## TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transit Association (APTA), *Transportation 2000,* also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA, the National Academy of Sciences, acting through the Transportation Research Board (TRB), and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

Because research cannot have the desired impact if products fail to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended endusers of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research. APTA will arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by urban and rural transit industry practitioners.

The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

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The members of the technical advisory panel selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and while they have been accepted as appropriate by the technical panel, they are not necessarily those of the Transportation Research Board, the Transit Development Corporation, the National Research Council, or the Federal Transit Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical panel according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

## Special Notice

The Transportation Research Board, the Transit Development Corporation, the National Research Council, and the Federal Transit Administration (sponsor of the Transit Cooperative Research Program) do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the clarity and completeness of the project reporting.

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# FOREWORD

*By Staff*
*Transportation Research Board*

This report will be of interest to transit specialists concerned with the safe operation of rail car doors in stations and to rail-station-facility designers seeking to incorporate car side-door observation aids in station facilities. The report provides documentation and analysis of a variety of approaches to rail car side-door observation. All aids currently used in transit practice are included, along with enhanced and new aids incorporating advanced technology. The intent of this research is to provide guidance for transit agencies seeking to implement observation aids. In addition, the research is targeted to transitfacility designers in that it suggests facility design practices to ensure optimal visibility of rail car side doors. The report includes recommendations for ways to enhance the effectiveness of observation aids and criteria for the selection of appropriate aids. In addition, the report provides a vision of the application of new and emerging technology to car side-door observation aids.

A previously published National Cooperative Transit Research and Development Program study (*NCTRP Report 13,* "Conversion to One-Person Operation of Rapid-Transit Trains") addressed the issues related to one-person operation of multiple-unit rapid-transit trains and identified car side-door safety as an important issue associated with this type of operation. The study suggested that certain work tasks can be performed by the vehicle operator more effectively with the aid of hardware or technology to observe the car side doors at both curved and straight platforms. Accordingly, there was a need to more fully explore the hardware and technologies available and provide guidance on their appropriate use.

Under TCRP Project A-3, research was undertaken by Telephonics Corporation to identify and evaluate various aids for car side-door observation and to develop guidelines to assist in the selection and deployment of devices best suited for specific applications.

To achieve the project objectives, the researchers conducted a review of rail car side-door observation practices, procedures, and devices in use in North American transit systems and in selected foreign systems. Visits were made to 17 transit systems to observe operations and collect data. In addition, data were collected from a number of foreign and domestic transit systems through a survey process. Based on this review, devices and techniques currently in use as well as experimental devices were identified and described. The overall merits of the identified devices and their suitability for specific applications were determined and guidelines for their use were prepared. To assist in the development of the guidelines, field tests of closed-circuit television, mirrors, and sensor-based door observation aids were performed. Thus, the report is a valuable resource for transit specialists considering the use of or improvement in aids for car side-door observation.

# CONTENTS

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This work was sponsored by the Federal Transit Administration and APTA's Transit Development Corporation and was conducted through the Transit Cooperative Research Program, which is administered by the Transportation Research Board of the National Research Council. The research reported herein was performed under TCRP Project A-3 by the Telephonics Corporation of Huntington, New York.

Clark Porterfield, Manager of Industrial Engineering, and Paul J. Smith, Systems Engineering Manager, were the investigators performing the research.

Mr. Porterfield was responsible for the operations, institutional, facilities, and statistical aspects of the work. Mr. Smith was responsible for the observation aids hardware equipment analyses and requirement definitions and the system integration aspects.

Credit must be given to the many transit property management, operations, and engineering personnel who found time to meet with the project team, accommodate requests for data, and provide tours of their facilities. In addition, credit must be extended to the numerous transit authorities personnel who took the time to respond to the questionnaire mailed to them. Also, particular note must be taken of the significant contribution made by the Port Authority Trans-Hudson System and the Maryland Mass Transit Administration, by allowing the use of their facilities and by providing personnel to support the project field demonstrations.

# .AIDS FOR RAIL CAR SIDE-DOOR OBSERVATION

## SUMMARY

Ensuring that rail car doors are clear before closing and train station departure has always been a significant safety issue in daily mass transit operations. Various approaches exist for performing side-door observation. These approaches range from the use of strictly manual procedures implemented by one or more persons to the use of automated observation aid devices specifically designed for the purpose. In general, the approaches taken by older transit properties were developed in the early days of their operations and, while they have evolved to some extent, they do not exploit available technology.

Because of increasing pressure to provide more cost-effective operations, transit systems are continually addressing worker productivity issues. Paramount among these issues is train crew size. Most of the older transit systems in North America operate with two-person crews and have achieved success with this technique. In a 1986 report (*NCTRDP Report 13*, "Conversion to One-Person Operation of Rapid-Transit Trains," the Transportation Research Board reported on increased interest in the conversion of trains to single-person operation. In this report, car side-door observation was ranked as the most significant issue associated with conversion. Since then, aids for car side-door observation have become increasingly important.

### REPORT SCOPE

This report presents the findings of a research program designed to a) evaluate current door observation practices and procedures and assess how they relate to transit property characteristics, such as facilities, vehicle configurations, and operating procedures; b) identify the range and scope of existing observation aids and assess their merits relative to their specific applications; c) identify promising observation technologies and define conceptual observation aids based on them; and d) develop guidelines for transit system use in the selection and implementation of observation aids for their specific application.

### RESEARCH

Much of the research effort concerned the collection of data on current observation practices and existing observation aids. The principal means for collecting these data were visits to 17 transit systems. This information was supplemented with informal visits to other locations where mass transit systems are in use, including major airports such as Pittsburgh, Atlanta, and Orlando. The researchers also used existing data for private locations with significant transit systems, such as the Disney World resort in Florida. The information collected by the researchers is broad in scope and covers various operational circumstances.

Although these visits focused on heavy rail operations because of their larger passenger volumes and more complex door observation scenarios, several sites included light rail and people-mover systems. While systems falling into the latter two categories are not generally subject to conversion to single-person operation, they are important because of the significant growth in the number of systems and passengers carried during the last 10 years. In addition, most people-mover systems are not staffed—making safety measures of great importance. At each site, many people, including operations, safety, and engineering personnel, were interviewed to obtain their views on door observation. Each of these functional disciplines has a unique perspective on door observation and observation aids, and any solution must address their requirements equitably.

In addition, these visits included first-hand observation of operations, characterization of the physical aspects of transit property facilities, and surveys of vehicle design and the general operating environment. Where observation aids were implemented by systems, their design, effectiveness, and the way in which they are incorporated in operating procedures and practices were studied in detail. Although there are differences from property to property, common characteristics link the transit systems. This commonality is the basis for the development of the recommendations and guidelines in this report.

The research team also reviewed transit-operations-related literature to collect information on research about observation aids. Although the researchers could not identify any literature relating specifically to the observation aid application, significant information was obtained on closed-circuit television (CCTV) and sensors, which are the basis of the conceptual observation aid system architectures detailed in this report. In addition, this literature contributed to the development of the usage guidelines for the observation aid systems, also included in this report.

Another significant part of the research was the demonstration of conceptual observation aid systems. Two such demonstrations were performed. The first of these addressed the use of sensor technology for a conceptual, sensor-based, autonomous observation aid. Although few sensor-based systems are used for door observation, this demonstration focused on the use of microwave motion sensors, which are new to the door observation application. This demonstration was performed on the Baltimore MTA's light rail system. For the demonstration, the researchers mounted the motion sensor in the door area of a vehicle. The researchers then rode the vehicle during normal operations to assess the ability of the sensor to detect passengers under various loading and operational conditions. Because sensor-based systems are intended to be autonomous and make their own decisions regarding door status, the researchers correlated the sensor observations visually with the actual door status. Although the researchers solicited information from transit authority operations personnel, the most significant information was provided by engineering and maintenance personnel. Operations personnel provided limited information because sensor-based systems are transparent to operations personnel and either send signals to the door control system or indicate to the train crews that the doors are clear to close; therefore, this report does not highlight the observations of the train crews relative to the sensor-based observation aid. This report does reflect the feedback of engineering and maintenance personnel, particularly regarding the issues associated with integrating the sensor-based aid with other vehicle systems, such as the door controls.

A second demonstration, addressing the use of visual-based observation aids (including mirrors and CCTV) was performed at PATH's Journal Square station in Jersey City, New Jersey. Although both of these technologies are used as observation aids, the demonstration addressed extensions to the existing technology base and structured usage guidelines. For CCTV-based observation aids, various system configurations were tested. These included systems with platform-mounted and vehicle-borne video monitors. As a result, this report provides information on various approaches to CCTV-based observation aids, thereby allowing transit properties to make cost-effective decisions that reflect their specific requirements. For the mirror demonstration, the demonstration efforts centered on making side-by-side comparisons of flat and convex mirrors and verifying guidelines for mirror positioning. These positioning guidelines must consider factors such as platform structural obstructions and the extent of the platform curvature. Because the demonstration location has a complex platform configuration with an S-curve platform edge and various structures, useful information was obtained.

Both demonstrations provided significant results. Generally, they were used to test the researchers' hypotheses regarding the application of observation aids. During this process, researchers obtained feedback from the users of the observation aids, i.e., the train conductors. As a result, the usage guidelines presented in this report are well tested and can be readily applied; however, these guidelines are not intended to, and in fact cannot, provide absolute guidance, because each transit system has its own operational and physical nuances that cannot be addressed by general guidelines. In synthesizing observation aid applications for their own use, transit properties should use these guidelines as a basis and tailor the system approach to their specific requirements. Where appropriate, this report provides guidance on this tailoring process.

## SYSTEMS VISITED

Because the systems visited included all of the heavy rail mass transit systems in North America, a broad sampling of data was obtained.

To support analysis, the systems visited (see the list in the Research Project Approach section of Part I, Chapter 1) were classified by age and by the physical and operational characteristics that influence door observation. These classifications are as follows:

- First-generation systems (pre-1950 vintage) such as NYCTA (New York), CTA (Chicago), MBTA (Boston), PATH (New York and New Jersey) and SEPTA (Philadelphia);
- Second-generation systems (1950s vintage) such as TTC in Toronto and Cleveland's GCRTA;
- Third-generation systems (post-1960 vintage) such as BART (San Francisco), PATCO (New Jersey and Pennsylvania), WMATA (Washington, DC), MARTA (Atlanta), MTA (Baltimore), Metrorail (Miami) and LACMTA (Los Angeles); and
- Fourth-generation unstaffed systems (1980s vintage) such as SkyTrain (Vancouver, BC) and Skyway (Jacksonville).

Each generation of systems has unique characteristics that significantly influence car side-door observation practices. As described below, some of these systems have multiple operations that exhibit multigenerational characteristics. For example, Miami has both heavy rail (i.e., Metrorail) and unstaffed people-mover (i.e., Metromover) systems. The classifications describe the bulk of the system's operations.

The first-generation systems are the most extensive in terms of track miles and number of stations. These systems illustrate characteristics that reflect the application of learning curves during their development. Older portions of these lines were designed to fit in the urban landscape and, as a result, have instances where station platforms exhibit curvature or have obstructions (e.g., structural columns). As these systems were extended into outlying areas, lessons learned were applied and station facilities were designed without curvature and obstructions. Trains operated by these first-generation systems typically feature manual train controls.

Toronto's TTC opened its first heavy rail operations in 1954 and, as a result, could take advantage, from its inception, of the lessons learned by its predecessors. The TTC station platforms are straight and virtually unobstructed, and the train controls are manual. Toronto operates its trains with two-person crews with the guard (conductor) performing door observation tasks. Toronto is a hybrid system—the Scarborough RT line has single-person crews and automatic train controls characteristic of third-generation systems. GCRTA also initiated operations in the 1950s and has straight, unobstructed platforms.

The third-generation systems were opened beginning in 1969, with the newest system in Los Angeles opening its first leg in 1993. These systems are characterized by generally straight, unobstructed station platforms; single-person crews; and automatic train controls. As a result, the basic characteristics of these systems facilitate door observation. Among these systems, PATCO has the most notable door observation aids and practices. PATCO extends from downtown Philadelphia to areas in southern New Jersey. The PATCO right of way includes the subway in Philadelphia, which was operated and abandoned by SEPTA's predecessor, and newly constructed right of way in suburban areas. Despite this reuse of subway right of way, PATCO stations exhibit characteristics that qualify it as a third-generation system. Some of PATCO's stations have curved platforms; however, the curvature is convex relative to the car side and, as a result, actually aids in door observation. At PATCO's Haddonfield station, platform structures, such as stairways, block the train operator's view of the rear of the train because of the curvature of the platform. PATCO has installed a CCTV-based observation aid to provide the operator with a complete view of the car sides. PATCO's operational procedures for this location dictate the use of the CCTV as the sole means of door observation, indicating PATCO's considerable confidence in the images that the CCTV provides.

The fourth-generation systems were opened starting in the 1980s and feature fully automated operation without crews on board the train. In addition to the systems listed above, the people-mover systems in airports, such as Atlanta and Orlando, qualify as fourth-generation mass transit systems. In these cases, door safety is provided by features designed into the rail vehicles and station facilities and by remote CCTV monitoring of operations.

These fourth-generation designs increase the passengers' responsibility for their own safety and security. This is not done blatantly—passengers are not told to use the system at their own risk—but subtly through passenger instructional materials such as signs and brochures and on-vehicle voice announcements. Generally, it appears that this approach can be implemented effectively on these newer systems. All of the fourth-generation systems visited have clean records relative to operational incidents. The researchers think that this approach is most suitable for newer systems and must be instilled as the operational culture of such a system. The passengers must learn how to use it and, if they are made responsible for their own safety at the outset, this responsibility will become ingrained. Elements of these approaches could be implemented on older, existing systems, but great caution would have to be exercised and passengers would have to be suitably educated. On these older systems, traditionally, passengers expect to have their safety attended to, consciously or not, and, as a result, often take unacceptable risks. For example, the researchers observed a passenger in an MTA-NYCT station attempt to pry open the closed doors of a train.

In addition to the heavy rail systems discussed above, the researchers visited several light rail systems. Usually, these visits were performed in conjunction with the heavy rail visits for those properties operating both types of systems.

The researchers visited six systems operating light rail vehicles. In general, light rail systems are characterized by single-person crews and manual vehicle controls. Because of the small size of light rail vehicles relative to heavy rail vehicles, factors such as platform curvature and obstructions do not have a significant impact. Most of these light rail systems use mirrors as the exclusive means of observing the vehicle doors.

## INDUSTRY VIEW OF DOOR OBSERVATION

For all systems visited, door observation is a significant operational safety issue. Each system visited has documented rules and procedures for the operation and observation of car side doors. In addition, several systems have implemented observation aids. Most systems view door safety as critical to maintaining ridership because of the high visibility that the mass media give to door-related incidents. Transit systems are also conscious of the costs of safety, and they budget considerable amounts to cover public liability claims. Because these costs can be addressed and constrained by safety measures, observation aids have become increasingly important in helping to reduce costs.

## STATE OF THE ART

Various observation aids are in use on mass transit systems worldwide. These aids include mirrors and various CCTV-based systems. Mirrors are used in virtually all major North American transit systems and are generally effective. Primarily, they enable the operator to see around obstructions on curved platforms and enable the train crew to observe the platform as the train leaves the station. Most of these mirrors are permanently mounted to station structures. The exceptions to this are mirrors mounted on the exterior of light rail vehicles. Although the research team found that station-mounted mirrors are generally effective, they are subject to vandalism, require accurate train positioning within a station, and present an image to the user that can distort the scene being viewed. This distortion occurs because a mirror provides a reverse image of the scene being viewed and, for convex mirrors, the image exhibits curvature conforming to the shape of the mirror. Convex mirrors also tend to shrink the image relative to what would be seen by the naked eye, which makes it difficult for the operator to discern details in the image.

Distortion is further compounded because the scene being viewed consists of converging lines (e.g., rail car sides and platform edges). As result, the person using the mirror needs to interpret the image being presented. This process requires experience in the use of the mirrors if the interpretation is to be made within extremely short dwell times. Despite their drawbacks, mirrors are suitable for various applications; however, care must be taken in their selection and installation.

The application of CCTV-based systems to rail car side-door observation is essentially in its infancy. Few of the systems visited employ CCTV and those that do make limited use of it. Of those systems using CCTV in North America, MTA-NYCTA has the most installations. In most cases, the CCTV installations do not provide complete coverage of the train and are intended only to supplement the train crew's direct field-of-vision. Conversely, a CCTV installation at PATCO's Haddonfield station provides complete coverage for the platform and is used to replace direct visual observation (i.e., opening the cab window and looking back at the train) by the train operator.

All of the significant North American CCTV installations use platform-mounted cameras linked to platform-mounted monitors. This is a limitation because trains of differing lengths will stop at different locations along the platform. As a result, only trains of a selected length can use the CCTV system. The sole exception to platform-mounted monitors is Toronto's TTC, which has mounted CCTV monitors in the cabs of a few rail cars as an experiment. For this system, radio frequency (RF) transmitters in the station send images to rail cars equipped with receivers and monitors. Similar CCTV systems are used by a few rail systems in Europe. In addition, SEPTA plans to use a similar system in the new rail cars it is purchasing for its Market-Frankford line.

As part of Toronto's CCTV experiment, two stations were equipped with video cameras and transmitters. Images are received and displayed in the cab, regardless of the train's stopping location in the station. While such a system has significant application to car side-door observation, Toronto's major purpose is to provide advance warning to the train operator of persons or objects in the right of way. This warning allows the train operator to stop the train before striking the person or object and thereby avoid major accidents and operational delays.

Depending on the number of cameras used, the monitor may display a split- or full-screen image. In some MTA-NYCT locations, two monitors are used to provide adequate coverage for trains up to 10 cars long. Where multiple cameras are used, the displays must be set up to ensure that the crew member viewing the images can maintain perspective. The research team found in viewing such CCTV-based systems that it was not always possible to determine exactly what portion of the train was being displayed.

As with mirrors, the effectiveness of CCTV-based aids depends heavily on the system application design and maintenance procedures. For example, one CCTV system observed had a camera that was out of focus, making the image displayed completely unusable. In another case, a camera was pointed so that half of the usable image it provided was of an electrical conduit. In both cases, minor changes and adjustments could significantly enhance the effectiveness of the system. CCTV-based systems offer numerous benefits, including advance warning of right-of-way incursions, enhanced viewing of doors at extreme distances from the operator's cab, and enhanced ease of observation during train departures.

During the site visits, it was clear that overall door-operating safety requires a systematic approach. This approach is the result of the interaction among such factors as operational procedures, equipment features, facility characteristics, and passenger behavior. Ensuring a high degree of door safety requires that transit systems address each of these aspects in detail. Although this report focuses on observation aid devices, it provides examples of how these other factors influence door observation.

For example, BART has installed platform edge tactiles as part of its Americans with Disabilities Act (ADA) compliance program. The tactiles warn visually impaired transit customers when they are approaching the edge of the platform. These tactiles are mostly bright yellow, approximately 18 in. wide, and extend the length of the platform. The tactiles also provide a high-contrast stripe (against BART's light-grey rail car sides and grey concrete station platforms) that can assist the train operator with door observation. Because BART trains can be up to 700 ft long, this contrasting stripe can provide significant assistance. Although primarily intended for ADA compliance, the tactiles enhance door observation.

## FUTURE DEVELOPMENTS

The sophistication of current technology embodied in door observation aids in North America is low. Mirrors as door observation aids, by their simple nature, will not realize any significant advance in the future. One possibility for mirror improvement is to make them out of materials that are resistant to vandalism. Also, because mirror location is critical, enhanced mounting methods that prevent shifting are desirable.

CCTV-based observation aids, on the other hand, have considerable potential for technological improvement. Several mature, off-the-shelf technologies could be applied to enhance the performance of these systems. One example is to employ enhanced RF short-haul video transmission links to send images directly to the cab of the rail car. Moreover, advances in RF technology have made data link hardware and installation requirements less costly while providing interference immunity and greater image clarity.

Another potential advance for CCTV systems is to employ flat-panel display monitors similar to those used in laptop computers. Space for equipment is at a premium in the cabs of rail cars. This applies to older cars with half-width cabs and even newer cars with transverse cabs. Conventional video monitors that use cathode ray tubes (CRTs) have considerable depth (approximately 14 in. for a 9-in.-diagonal screen), which makes installing them a challenge. Flat-panel displays, on the other hand, can be produced in a package with a depth of less than 4 in. for CCTV monitor applications.

CCTV systems can also be improved in terms of image processing. Rarely can a single CCTV camera provide sufficient visibility of the sides of a rail car to ensure that the doors are clear. Such cases require that the images be combined to provide the train crew with a complete picture. Advances in video image processing provide considerable potential to do this. Most notable is the availability of hardware that allows up to four images to be merged into a single picture with real-time, live video. This enables the train operator to view the entire side of the train at one time on a single monitor.

In addition to the mirrors and CCTV in use, a completely new class of observation aids can be developed. The mirrors and CCTV provide an image to a member of the train crew who then uses this information to determine if the car doors are clear. An alternative form of door observation aid could be designed to eliminate the person in the loop. Such a system can use proximity-detecting technology, such as ultrasound or microwaves, to determine if the area of the car doors is clear.

The required sensor technology is mature and in widespread use in such critical applications as security, industrial process control, and vehicle collision avoidance. Sensor-based observation aids are highly appropriate for application to unstaffed systems, such as Vancouver's SkyTrain or the various people-mover systems, but could also be applied to staffed operations, such as light rail systems. The outputs of the sensors would be connected to a microprocessor-based controller, which would have the necessary logic to interpret the sensor outputs and make decisions regarding door status. Outputs from the controllers would be trainlined and routed to the active cab where an indicator could be provided for train operator use. For automatic applications, the controller outputs could be integrated into the overall train movement control logic. Although this study program demonstrated and validated the application of sensor technology, considerable additional work could be done in this area. Essentially, this work should focus on the system and system integration aspects of an autonomous observation aid. For example, where multiple sensors are used, they will need to be interrogated in synchronization with the door control system. This will require a timing sequence for sensor interrogation. In addition, integration of the observation aids with other rail vehicle systems needs to be considered. Depending on the system configuration, the autonomous aid can be integrated with the door control, communications, and other systems.

## OBSERVATION APPROACH SELECTIONS

Through the site visits, distribution of questionnaires, and research of various technologies, the researchers have identified four different observation approaches. Variations on some of these types raise the number of potential approaches to seven. The seven types are as follows:

- Direct visual observation (unaided),
- Vehicle-mounted mirrors,
- Platform- and station-mounted mirrors,
- CCTV with platform-mounted video cameras and monitors,
- CCTV with vehicle-mounted monitors and platform-mounted cameras,
- CCTV with vehicle-mounted monitors and cameras, and
- Automatic sensor-based observation aids.

Selecting an appropriate observation approach is a fairly complex matter, which must address various factors, including vehicle characteristics, crew sizes, and station facility

**TABLE 1 Observation and selection decision matrix**

| ASSESSMENT CRITERIA | DIRECT VISUAL OBSERVATION | MIRROR VEHICLE-MOUNTED | MIRROR PLATFORM-MOUNTED | CCTV PLT MON PLT CAM | CCTV VEH MON PLT CAM | CCTV VEH MON VEH CAM | SENSOR-BASED SYSTEMS |
|---|---|---|---|---|---|---|---|
| TYPE OF OPERATIONS | | | | | | | |
| LIGHT RAIL | x | x | x | | | x | x |
| HEAVY RAIL | x | | x | x | x | x | |
| PEOPLE MOVER | | | | | | | x |
| CREW COMPLEMENT | | | | | | | |
| SINGLE PERSON | x | x | x | x | x | x | x |
| MULTIPLE PERSON | x | x | x | x | x | x | x |
| UNMANNED | | | | | | | x |
| FACILITY CHARACTERISTICS | | | | | | | |
| CURVED PLATFORMS | | | x | x | x | x | x |
| OBSTRUCTED PLATFORMS | | | | | | | x |
| MULTI-BERTH PLATFORM | x | x | | | x | x | x |
| VEHICLE CHARACTERISTICS | | | | | | | |
| SINGLE UNIT | x | x | | | | x | x |
| MULTIPLE UNIT | x | x | x | x | x | x | x |

characteristics. The rest of this report provides information that will assist transit operations personnel in assessing their operations in detail and in making appropriate decisions.

Table 1 provides initial guidance for readers on approaches that are most appropriate to their situations. This table is a decision matrix that indicates which observation approaches are generally appropriate for various system operations. The table is not intended to provide absolute guidance, only to suggest approaches for further consideration. For example, the table indicates that platform-mounted mirrors are suitable for use on curved platforms; however, the severity of curvature must be considered. Mirrors will work with slightly currved platforms, but CCTV is probably required for stations with severely curved platforms.

When reviewing the information in the table, readers should seriously consider only approaches that meet all criteria. For example, for a heavy rail system with single-person crews and curved and obstructed platforms, the three CCTV-based approaches are most suitable. Although platform-mounted mirrors are suitable for use with heavy rail operations, they generally will not work on obstructed platforms. Similarly, sensor-based systems are suitable for obstructed platforms but not for heavy rail operations.

# PART I—Executive Overview

CHAPTER **1**

# INTRODUCTION AND RESEARCH APPROACH

## PROBLEM STATEMENT AND RESEARCH OBJECTIVES

Because of increasing pressure to operate more cost-effectively, transit systems are continually addressing worker productivity issues. Paramount among these issues is train crew size. Although most of the older transit systems continue to operate with two-person crews, newer systems have initiated service with single-person crews and operate successfully. In a 1986 report (*NCTRP Report 13*, "Conversion to One-Person Operation of Rapid-Transit Trains"), the Transportation Research Board reported on increased interest in the use of single-person crews. Since the publication of the report, cost-cutting pressure has increased and more transit systems have developed plans to convert. In the 1986 report, car side-door observation was ranked as the most significant issue associated with conversion. As a result, aids for car side-door observation have received greater interest.

The principal objectives of this study are the following:

1. Evaluate door observation practices and procedures currently employed by transit systems (Although research focused on site visits to North American systems, questionnaires were forwarded to several foreign systems for additional data.);
2. Identify promising observation technologies and define conceptual observation aids that use them as a basis; and
3. Develop guidelines for transit system use in the selection and implementation of observation aids for their specific application and validate these guidelines through the performance of two demonstrations at transit properties using conceptual observation aids.

The ultimate goal of this study was to develop a guide for transit authorities to use in evaluating observation aid requirements, selecting suitable technology, and implementing the aids so as to provide maximum effectiveness. No specific recommendations are made for individual transit systems relative to observation aids. These decisions are left to transit authorities to make on the basis of their own specific requirements.

## BACKGROUND

Ensuring that rail car doors are clear before closing and train station departure has always been a significant safety issue in daily mass transit operations. Various approaches exist for performing side-door observation. These approaches range from strictly manual procedures implemented by one or more persons to automated observation aids specifically designed for the purpose.

As a cost-management measure, several transit systems have converted train crews from two people to one person. Where conversion to single-person operation is performed, the workload of the sole crew member must be reduced. Providing car side-door observation aids significantly reduces this workload while the train is in a station.

Observation aids are used on most systems operating multiple-unit rapid transit trains; however, use of observation aids is not widespread and does not take complete advantage of the available technology. Although transit systems confirm that these aids contribute to overall safety, questions—about reliability, cost-effectiveness, and the true extent to which these devices contribute to passenger safety—remain. Furthermore, no two transit systems are exactly alike. They differ in their operations, equipment, and facilities, so it is impossible to generalize about the effectiveness of an observation aid.

The goal of this research project is to investigate observation aids and to provide the transit industry with a comprehensive reference source. This reference is designed to allow transit personnel to fully understand the requirements of their specific application and select an appropriate observation aid.

## RESEARCH PROJECT APPROACH

Much of the project effort concerned the collection of data on existing observation practices and aids. Researchers collected data primarily by visiting 17 transit properties. While these visits emphasized heavy rail operations, because of their larger passenger volumes and more complex door observation scenarios, several properties included light rail and people-mover systems. During each visit, the researchers interviewed numerous people (including operations, safety, and engineering personnel) to obtain their views on door observation. In addition, these visits included first-hand observation of operations, surveys of the operating environment, surveys of vehicles, and characterization of facility attributes.

Where observation aids were implemented by systems, their effectiveness and the way in which they were used by operating personnel were reviewed. The research team also reviewed transit operations and related literature to collect information on prior research about observation aids.

The systems visited were selected to include a suitable cross section of multiple-unit rapid transit systems. This cross section was designed to include a mixture of single- and two-person crews, automatic and manual train controls, and old and new system designs. The specific systems visited were the following:

1. Bay Area Rapid Transit (BART)
2. Los Angeles County Metropolitan Transportation Authority (LACMTA)
3. Jacksonville Transportation Authority (Skyway)
4. Metro-Dade Transit Agency (Metrorail and Metromover)
5. Metropolitan Atlanta Rapid Transit Authority (MARTA)
6. Chicago Transit Authority (CTA)
7. Maryland Mass Transit Administration (MTA)
8. Massachusetts Bay Transportation Authority (MBTA)
9. Port Authority Transit Corporation of Pennsylvania and New Jersey (PATCO)
10. Metropolitan Transportation Authority—New York City Transit (MTA-NYCT)
11. Port Authority Trans-Hudson System (PATH)
12. Greater Cleveland Regional Transit Authority (GCRTA)
13. Tri-County Metropolitan Transportation District (TRIMET), Portland, Oregon
14. Southeastern Pennsylvania Transportation Authority (SEPTA), Philadelphia, Pennsylvania
15. Washington Metropolitan Area Transit Authority (WMATA)
16. British Columbia Rapid Transit Company (BC Transit)
17. Toronto Transit Commission (TTC)

In addition to visiting these systems, a questionnaire was developed (see Appendix A), which was distributed to additional systems. Although the research emphasized heavy rail mass transit operations, the circulation of the questionnaire included selected commuter rail and light rail operators because these properties have the same observation issues.

Generally, the visits included discussions with personnel representing the appropriate functional disciplines. Visits were coordinated with members of the project panel, persons recommended by the panel, or personnel identified via transit industry directories. In each case, the information required for the project was discussed with these points of contact to ensure that the goals of the visit were met.

These discussions included personnel from one or more of the following disciplines:

- System operations,
- Rail operations,
- Equipment engineering and maintenance,
- Safety,
- Training, and
- Operations.

The purpose of these visits was to collect the following minimum information:

- Rail property characteristics (e.g., types of operations, right-of-way locations, and operational statistics),
- Door incident statistics and characteristics,
- Operational procedures (e.g., crew sizes and door observation procedures),
- Facility characteristics (e.g., platform length, degree of curvature, and lighting),
- Observation aid types and applications (e.g., mirrors and CCTV),
- Additional safety features,
- Safety procedures, and
- Training/operator certification.

At the meetings, the questionnaire (Appendix A) was used as the basis of discussion to ensure that the required data were obtained. The questions usually led to detailed discussions of operations, equipment, and other project-related topics. Following the meetings, various systems facilities were toured to highlight elements of the discussion and to observe operations first hand.

In all cases, the researchers rode the trains of the systems to view facilities and observe the actions performed by train crew members. Where the systems were using observation aids, installation locations for each type were visited. At these sites, detailed evaluations were made of each device's characteristics, installation, and effectiveness. As part of the effectiveness evaluations, several train operators were observed using the device during normal operations. The observations made during this activity provided significant information for use in assessing the merits of the aids. In addition, viewing how observation aids are used helped the researchers develop guidelines for their application.

A multifaceted approach was used to review conceptual aids. This included assessing the possibility of advances in existing aids and of development of completely new classes of aids. Consideration was given to the current state of rail operations as well as the direction of future developments.

First, a review was made of the mirrors and CCTV systems currently in use. Because mirrors are simple in nature, their potential for development was found to be very limited. Relative to the mirror itself, beneficial changes would make them less prone to damage from vandalism. Through the use of advanced materials, such as high-impact plastics, mirrors can be made resistant to breakage.

The CCTV systems in use are relatively simple in nature and have considerable potential for development. This development potential includes both system components and the general system architecture. During the research effort, discussions were held with manufacturers of CCTV components and organizations integrating CCTV systems for specific customer applications. The research was discussed, and views were solicited relative to the use of CCTV in the door surveillance application. As a result of these discussions, recommendations were made, which contributed to the development of the conceptual CCTV observation aids detailed in this report.

To verify these recommendations and to develop specific guidelines for the use of CCTV in the door observation application, a demonstration was performed at PATH's Journal Square station in Jersey City, New Jersey. During the demonstration, a conceptual system was temporarily installed and response was solicited from observation aid users. For PATH, these users were the train conductors. The basic system demonstrated used color images and had platform-mounted monitors making it different from any CCTV-based observation aid seen during the site visits. For a short time during the demonstration, the system was reconfigured to provide transmission of platform images to the rail car via an RF transmission link. In this way, the researchers were able to verify the feasibility of the bulk of the technology base addressed in this report. Where applicable, commentary on the demonstration findings has been incorporated in this report. In addition, Appendix E is a description of the events surrounding the demonstration.

In addition to reviewing the development potential for existing aids, the research team addressed the development of new aids. All existing observation aids rely on visual techniques and require that the train crew view and interpret images of the rail car sides. On the basis of a broad review of technology and transit industry developments, the researchers elected to evaluate alternate systems that are fully autonomous and make their own determinations of door status.

Such systems are applicable to staffed operations with single-person crews and unstaffed operations. In simple terms, the architecture of these autonomous systems will consist of sensors and a processor to interpret the sensor outputs. In evaluating the requirements, it was determined that the sensors are the critical elements of these systems, because their nature will dictate the required processing methodology and technology.

A broad-based review of sensor technology indicated that both proximity and motion sensors were appropriate for the door observation application. Proximity sensing has an extensive history of use in industrial process control systems for various applications. Investigation of proximity sensors revealed that various types are designed to sense materials with varying properties.

Because the requirement is to sense people and their personal effects (e.g., clothing, parcels, bags, and strollers), several sensor types, such as those used to sense ferromagnetic properties, were immediately eliminated from consideration. As was the case during the study of CCTV-based systems, sensor manufacturers were contacted to review the door observation application and the manufacturers made specific recommendations.

On concluding the sensor investigation, the researchers determined that photoelectric proximity, microwave proximity, ultrasonic proximity, and microwave motion sensors warranted further consideration. Samples of the microwave and ultrasonic sensors were obtained and were laboratory tested under simulated conditions corresponding to those that would be experienced during transit operations.

Testing of photoelectric sensors was conducted at the facility of a local manufacturer of the devices. The laboratory testing results indicated that photoelectric proximity and microwave motion sensors were best suited to the observation aid application. Because of their greater complexity, microwave motion sensors were selected for use during the sensor demonstration. This demonstration was conducted on the Baltimore MTA's light rail system and consisted of installing the sensor in the door area of a vehicle and observing its response to actual operational conditions.

The researchers rode the vehicle during this test and correlated the sensor output to the state of the door area visually. Sensor-based observation aids are designed to be autonomous—they will make decisions regarding the status of the doors without human input. For this reason, the researchers did not solicit the opinions of train crews but relied on the views of operations, engineering, and maintenance personnel. Details of the results of this demonstration and the lessons learned are included in Part I of this report in the section dedicated to conceptual observation aids.

Although the researchers believe that sensor-based observation aids are realistic and feasible, further research should be done before they can be implemented. As detailed in Part I, actual sensor-based observation aids should employ both motion- and proximity-sensing technology. Processing is required for the sensor outputs. This processing must consider the door closure process and, as a result, the observation aid must be integrated with the door control system. While not overly complex, this integration will require further research, particularly to develop the timing scheme for the interrogation of the dual sensors. Information provided in Part I of this report provides a good basis for this research, including timing diagram and installation requirements for a combined motion/proximity sensor-based observation aid.

Part II of this report contains the supporting technical information of the properties visited.

CHAPTER 2

# FINDINGS AND INTERPRETATION

## THREAT TO PASSENGER SAFETY

Prevention of passenger injuries is a significant issue in daily mass transit operations. Door-related injuries can seriously affect the overall timeliness of transit operations because of delays associated with emergency services activities and accident investigations. Such injuries influence overall passenger perception of mass transit and can lead to negative opinions about transit ridership. Such injuries receive high-profile treatment from the news media, which contributes to the development and spread of these opinions. Therefore, promoting and maintaining safe door operation is of paramount importance.

Interaction between passengers and any form of transportation system is, by nature, an accident waiting to happen. These accidents can occur because of failures of operating equipment or from the failure of passengers or train crews to exercise due caution. Often, these incidents occur because of a combination of factors.

At the inception of the project, the researchers had developed hypotheses about the threat to passenger safety that the door observation aids need to address. One goal in the distribution of the transit authority questionnaire and the transit property visits was to test these hypotheses and, as appropriate, expand and refine the definition of the threat.

In general, the transit systems could characterize the types of door-related injuries, but few could provide statistical information. Nearly all questionnaire respondents and properties visited collect data on the number and type of reported incidents, but they do not distinguish door-related accidents from other accidents that occur in the stations. Thus, only limited information from a few transit systems was available for review. Although the results are not applicable to all transit properties, the results permit some general discussion and the identification of areas of concern in passenger safety. The following paragraphs provide information made available to the researchers during the effort. The data were classified and qualified by incident characteristics, and specific potential threats to passenger safety were identified.

## INCIDENT ANALYSIS

### Calgary Transit

Calgary Transit furnished descriptive data about 11 door-related incidents that occurred between January 1991 and September 1993. In reviewing the one-line summary of the computer-logged and -compiled data, several classifications can be made.

Two incidents were directly related to mechanical problems with the doors. One event was related to a passenger catching a foot in the gap between the platform and the train door. Four cases involved the doors striking a passenger or breaking an object. Three situations concerned a passenger or object becoming caught in the doors. The final incident involved a passenger catching a hand in the door hinge. Further investigation of the detailed causes of each case would be helpful in recommending corrective measures.

### BC Transit

For the BC Transit SkyTrain unstaffed operation, no dragging incidents related to door operation or observation have occurred to date in its service history. Unfortunately there have been 13 fatalities, all classified as suicide. The final seven were verified because they occurred after recording equipment was added to capture video images from the platform-mounted CCTV cameras. While BC Transit has sensors to detect people in the trackbed, these sensors cannot prevent or protect someone from jumping into the path of a moving train.

### Metropolitan Transportation Authority—New York City Transit

MTA-NYCT collects basic statistical data on reported incidents for subsequent analysis to identify areas of concern. The data supplied during investigations define 516 door-related incidents from 1988 through September 1993. On average, 92 incidents occur yearly.

The data provided include such information as the date and time, location, passenger load level, platform configuration, number of mirrors and CCTV monitors at the station, and an abbreviated description of the incident. This description summarizes the door-related incident by distance dragged (if any), whether or not there was a claimed injury, and a comment identifying the type of incident (e.g., child, object, baby stroller, coat, intoxicated, blind person, and fatal). The total incidents represent slightly more than 0.0001 percent of the entire 500 million passengers transported during the 5 years.

### Toronto Transit Commission

TTC's Safety and Security Department collects data for incidents that occur on their three heavy rail transit lines. The information furnished includes descriptive analyses of incidents and identification of equipment failures that contributed to the accident. From January 1992 to July 1993, there were 82 incidents. Of these, two resulted from faulty door control systems. Thirteen incidents involved passengers exiting the train and being struck or caught by the doors. Thirty-one incidents were related to passengers boarding the train and being struck or caught by the closing doors. (Four of these boarding incidents involved passengers running to board the train as the doors were closing.) An additional 31 injuries were caused by passengers becoming caught between the doors and the door jamb as they were opening. TTC has initiated awareness programs and has installed warning signs admonishing passengers to stand away from the doors, to minimize the incidence of injuries where hands become caught as the doors open.

## SUMMARY OF THREAT TO PASSENGER SAFETY

In summary, the interaction between passengers and the operation of transit systems poses inherent risks to passenger safety. Four major areas of concern are evident from analyzing the data furnished by the transit systems and from the observations made during the site investigations. These are as follows:

- Passengers caught or struck by closing doors during normal boarding,
- Passengers attempting (running) to board the trains when the doors are closing,
- Observation and detection of passengers caught between closed car side doors, and
- Observation of emergency conditions on station platforms during station approach and station departure.

Train crews must be able to identify and respond to each of these situations if passenger safety is to be assured. The true effectiveness of rail car side-door observation aids must be measured by how they help train crews address these areas of concern.

## OBSERVATION REQUIREMENTS

The observation of transit car side doors must address several primary and secondary factors to ensure reliable, safe passenger boarding. Attentive, thorough observation on the part of the train crew and the application of fail-safe operations in automatic unstaffed systems are critical to addressing these factors.

## OBSERVATION PROCEDURES

Five basic steps occur every time a train enters the station. Each step consists of a function and a related observation. Figure 1 illustrates the five functions and the related observation requirements.

As the train approaches the station, the operator observes the platform and track for situations requiring emergency action. With the train stopped, the train operator and the person responsible for door operation (if different) observe that the train is properly berthed in the station and that the doors are aligned with the platform. Proper berthing may be determined through observation of wayside stopping-location markers or by similar identification systems.

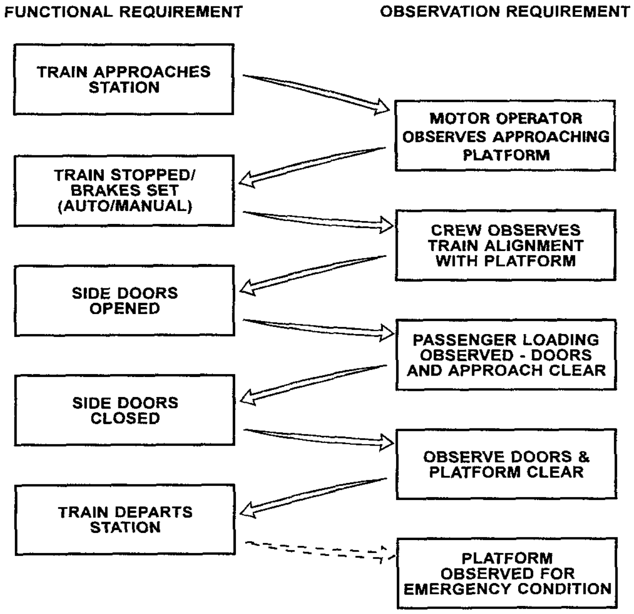


*Figure 1. Generic car side-door observation requirements.*

With the train doors open, the person responsible for door operation will observe passenger loading and unloading. When this is completed or at the end of the standard dwell time, the doors are closed. The passenger unloading and loading process can actually be broken into three phases. First, passengers disembark from the train; second, passenger boarding begins—these two events often occur simultaneously, particularly during peak periods. Finally, late-arriving passengers rush to board the train before or during door closure. The latter two of these phases are of primary concern in car side-door observation. The first phase does not normally warrant a high level of concern—it is rare for passengers to wait to disembark from the train until the doors are closing.

Two steps are required for the safe closure of car doors. The first is to ensure that no object (e.g., a person, an article of clothing, or a stroller) is between the doors before the activation of the door closure controls. The second step is to ensure that no person or article will become lodged between the panels while the doors are closing.

### Clear Door Panels

Ensuring that the area within the sweep of the door panels is clear before closure is essential in providing safe operation on rapid transit systems. The intersecting point of the door

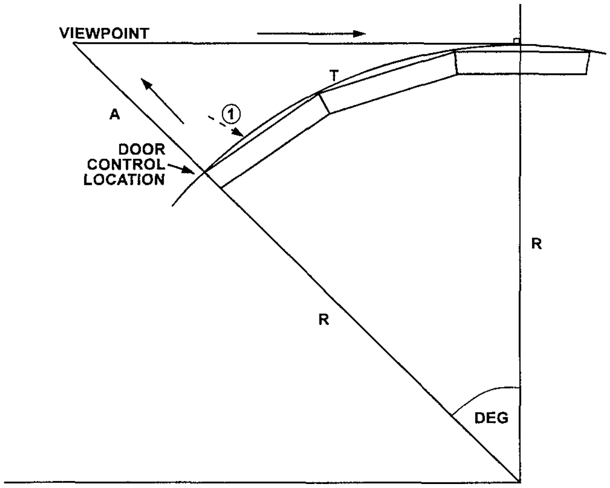


*Figure 2. Dimensional representation of viewpoint distance on platform curvature.*

panels is the critical area where persons can become caught and possibly injured. The approach most commonly used in today's systems is to observe along the plane of the car side to identify any object protruding from the door areas. This may be accomplished by direct observation from the operator's position or indirect observation using observation aids. The field-of-vision (also referred to as field-of-view) for these observations runs parallel to the side of the rail car and is essentially perpendicular to the direction of travel that passengers use in entering or exiting the car.

The operator can readily make observations in the required field-of-view when the edge of the platform is a straight line. This is also true when the platform edge has a convex curvature and no significant obstructions exist within the field-of-vision. In this case, the ends of the rail car are closer to the train crew's position than in the case of a straight platform, thereby facilitating observation. In the opposite case, where the platform edge is concave, the severity of curvature can impair the operator's ability to see the doors.

For a single car or vehicle train, the outside edge where the doors are located is always a straight line. Operators can observe the entire length by leaning out the cab window a minimal distance. For two or more cars per train, the distance that operators can observe is a function of the curvature of the outside edge of the train and the linear distance they lean out the window. By leaning out the window of the rail car, operators project their viewpoint from the side of the rail car allowing them to see around the curvature. Similarly, an observation device, such as a mirror or CCTV camera, can be placed to obtain the required viewpoint projection. (Figure 2 represents the relationship between the viewpoint projection and the viewing distance.)

Appendix B of this report contains a Microsoft Q-Basic Program which calculates the required viewpoint projection in terms of the length of the train and the radius of the platform curvature. For purposes of the calculations, the viewpoint projection is defined as being perpendicular to the door control location. This distance represents the extent that an operator would need to lean out the cab window or the point where an observation aid should be located to provide the necessary viewing area. This program can be run for trains of any length and with various door control and observation locations. In addition, Appendix B contains the mathematical derivation and basis for the calculations performed within the program. When using the output of the program in designing an observation aid application, the user is cautioned to carefully consider any obstructions between the viewpoint location and the side of the rail vehicle.

Figure 3 is a graph of the output produced when this program is run for various train configurations. In this figure, the greater the viewpoint projection away from the side of the rail car, the greater the allowable radius of platform edge curvature. Where the required projection exceeds 2 ft, some form of observation aid will be required because it will be impossible for the average train crew member to lean out the window further than 2 ft. Mirrors are generally used where minor platform curvature or facility structures exist that restrict the operator's field-of-view along the edge of the car. These devices are installed in a position to allow the operator to view the obscured doors through a perpendicular approach to the direction of travel by passengers through the car doors. The mirrors are generally located within 6 to 8 ft of the position of the person responsible for door operation, although distances of 12 to 14 ft were observed during the site visits. At the greater distance, the effectiveness of the mirrors decreases, because it becomes difficult to observe the images projected by the mirror, and detail is lost because the image appears smaller. However, the greater distance does provide an increased field-of-view that includes those doors and vehicle features closest to the location of the person responsible for door operation.

CCTV-based observation aids are used where platform curvature is more pronounced or where there are significant platform structures or features that obstruct visibility. Where a CCTV-based observation aid is used, the camera can be located anywhere, as long as the monitor is close to the viewer. Monitor location recommendations are provided in the Observation Aid Usage Guidelines in Chapter 4. Generally, the location of the monitor relative to the viewer's position is a function of the diagonal size of the monitor.

Generally, the rail vehicle is berthed with the location of the person responsible for door operation perpendicular to the viewpoint. This is illustrated as Scenario A in Figure 4. Because the berthing locations can vary, especially when operating under manual control, any change in angle from perpendicular alignment can affect the observable distance. If the train stops short of the intended berthing location, the change in angle will reduce the overall observable distance. In addition, observation aids placed at the normal berthing location will have their usability diminished or will be unusable. Scenario B in Figure 4 depicts this situation. In this case, the operator's ability to observe the doors on the rear car will be impaired, because

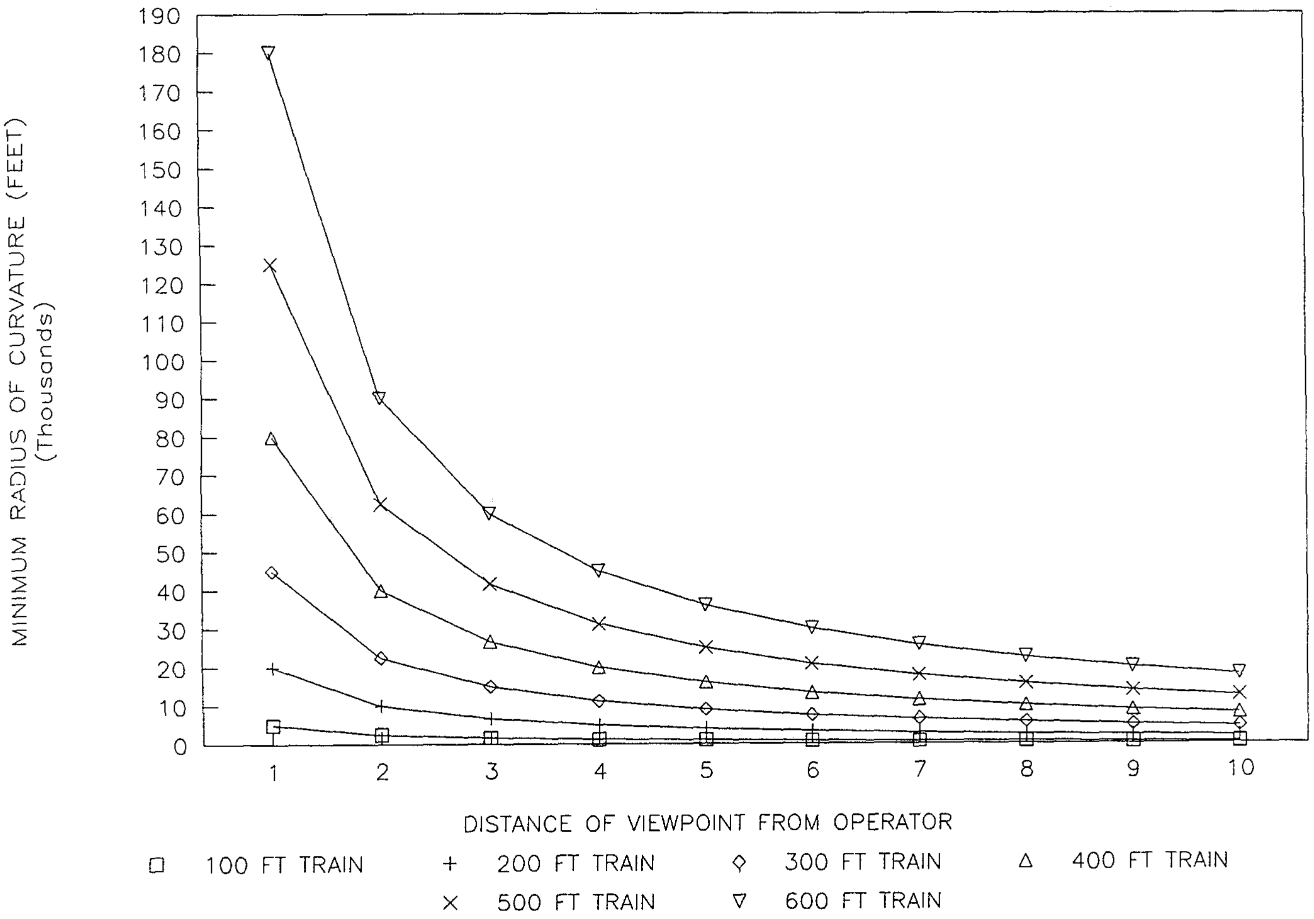


*Figure 3. Graphical representation of minimum allowable radius for curved platforms.*

the tangent line of the outer surface of the rear car no longer intersects the viewpoint location.

If a train berths beyond the viewpoint alignment location (as shown in Scenario C of Figure 4), the observable length along a given train would appear to increase for a fixed platform curvature radius. This actually depends on the characteristics of the device located at the viewpoint. Assuming a mirror is used, the person responsible for door operation may still be able to see a sufficient amount of the train.

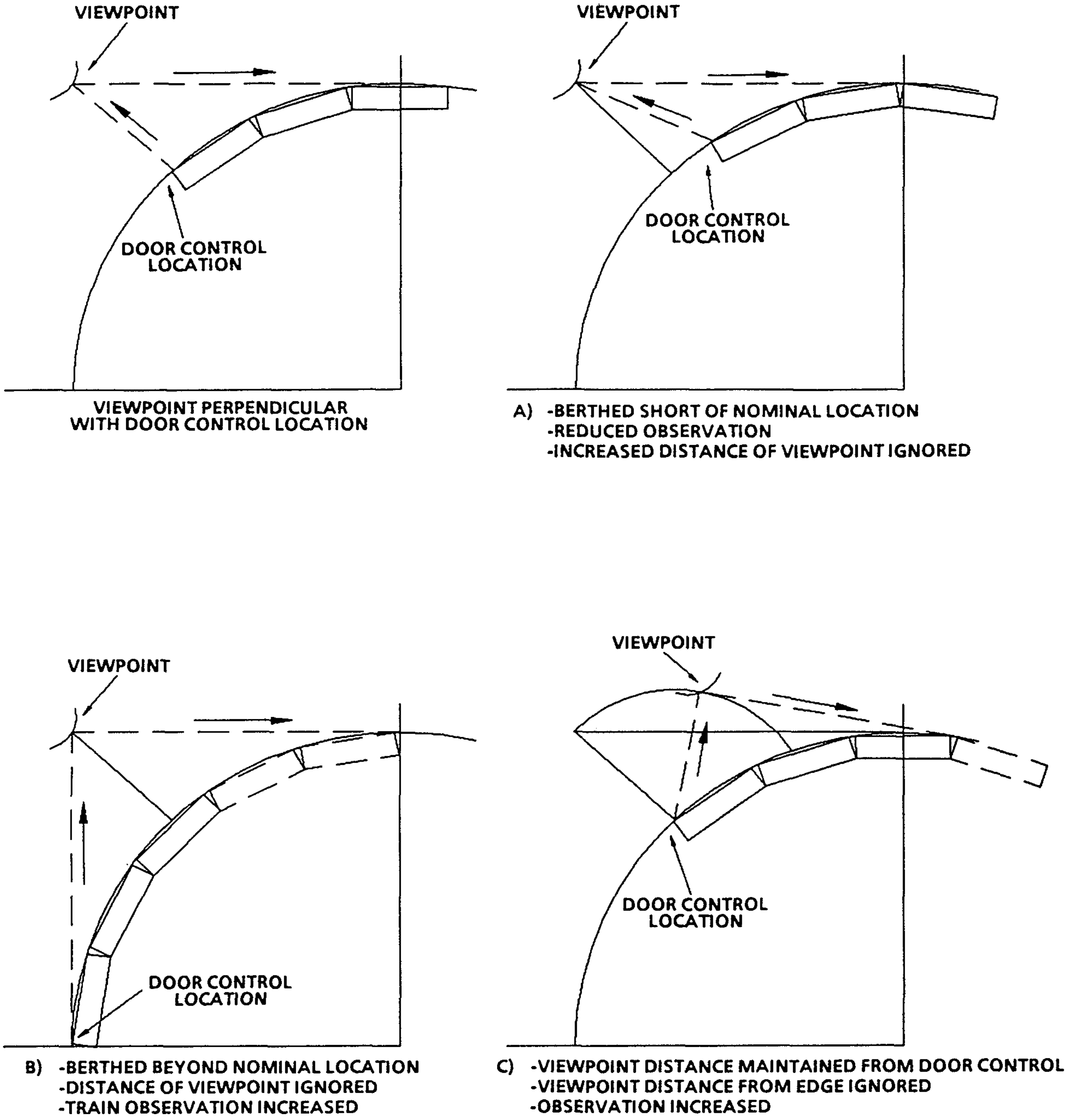
Assuming the distance from the viewpoint to the control position is maintained and the distance from the edge of the platform is ignored, then the potential observable distance will increase. This situation is illustrated in Scenario D of Figure 4. Assuming a convex mirror is employed, this situation can be desirable. For a given radius, the increase in observable train distance can be calculated on the basis of the line depicting the distance from the viewpoint to the rear car when tangent to the corresponding tangent points of the two radii.

The variations illustrated in Scenarios C and D of Figure 4 do not consider any degradation in the effectiveness of the device from the compression or distortion of images from the increased angle of incidence when using convex mirrors or the reduction in observable area when using a flat-faced mirror. In addition, degradation resulting from the increased distance between the person responsible for door operation and the device located at the viewpoint must be considered.

### *Structural Obstruction Offset*

The preceding calculations are predicated on platforms that have limited or no obstructions in the field-of-view. Although this is true of many stations, many concave platforms contain columns, facility structures, or both that restrict a clear field-of-view of the car side doors. Figure 5 illustrates this situation as seen during one of the site visits.

The columns in this location were in a line approximately 3 ft from the platform edge. For a curved platform, the proximity of the columns or structures to the edge of the platform can severely affect the operator's ability to observe the side doors on the cars furthest from the viewpoint. In addition, it can severely restrict the distance that the viewpoint can be set back from the edge of the platform as calculated using the Q-Basic Program of Appendix B. Where the viewpoint setback conditions cannot be met, it is most often necessary to employ a CCTV-based observation aid with multiple cameras.



VIEWPOINT PERPENDICULAR WITH DOOR CONTROL LOCATION

A) -BERTHED SHORT OF NOMINAL LOCATION
-REDUCED OBSERVATION
-INCREASED DISTANCE OF VIEWPOINT IGNORED

B) -BERTHED BEYOND NOMINAL LOCATION
-DISTANCE OF VIEWPOINT IGNORED
-TRAIN OBSERVATION INCREASED

C) -VIEWPOINT DISTANCE MAINTAINED FROM DOOR CONTROL
-VIEWPOINT DISTANCE FROM EDGE IGNORED
-OBSERVATION INCREASED

*Figure 4. Impact of train berthing on fixed viewpoint observational area.*

From a facility design standpoint, obstructions near the edge of a platform will restrict the extent to which the platform may be curved. The minimum distance that a structure can be offset from the edge of the platform without affecting the field-of-view can be calculated, using, as the basis, a derivative of the mathematical process described in Appendix B. This process will calculate the distance between the side of the rail car and the tangent to the curvature of the rail car side that intersects the viewpoint.

As discussed in the following section, a minimum clear area along the platform edge extending from the doors is defined in order to ensure that the doors are clear before and during closure. The size of the area depends on the operational and vehicle characteristics of the specific transit system. Figure 6 illustrates this zone in terms of the viewpoint setback and platform curvature in the area bounded by line, *OSL*, and the arc, *T*, in the figure. It is possible to calculate the distance between the car side and the setback line in terms of the vehicle configuration, platform curvature radius, minimum offset point, and vehicle setback. Appendix C is a Microsoft Q-Basic pro-

*Figure 5. Columns near platform-edge obscuring conductor's vision on MTA-NYCT train.*

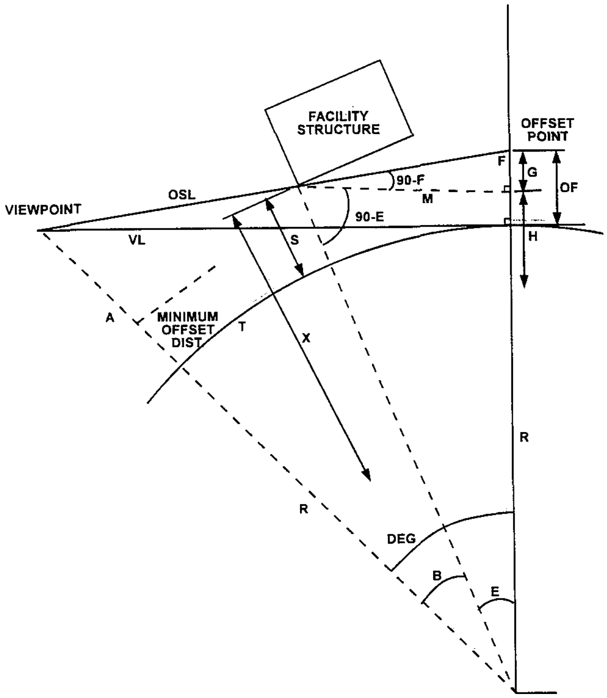


*Figure 6. Dimensional representation of platform structure impacting offset zonal coverage.*

gram, which performs these calculations. In addition, the appendix contains the mathematical derivation and basis for the calculations performed within the program.

Generally, this program is designed to be most useful to transit facility designers as they plan the location of platform structures, which can obstruct door observation. Where an existing facility is being evaluated, the program of Appendix B will be of more use. In this case, any significant obstructions in the field-of-vision will dictate the need for a CCTV-based observation aid with multiple video cameras.

The distances calculated by the program of Appendix C are based on the minimum radius of curvature of the platform for the variable train lengths. Where the platform edge has a complex curvature, the portion with the smallest radius will have the most significant impact on observation requirements. The minimum offset point is also a variable within the program and can be adjusted according to the operational requirements of the specific transit system. Generally, this offset distance should not be less than 2 ft and, in reality, should be as large as possible to allow early detection and observation of passengers running to enter closing doors. Figure 7 represents the minimum allowable structural offset for a train 100 ft long for two minimum offset distances: one of 2 ft, and one of 4 ft.

### *Offset Observation Zone*

The area outside the vehicle, in front of the doors, is of major significance in the safe operation of car side doors. This area is referred to as the offset observation zone. To account for the varying angles of passenger entry into the vehicle, this area will be fan-shaped, extending from the door area. Although the area between the door panels may be clear, passengers approaching the rail vehicle can enter the space between the door panels as they are closing. In this way, ensuring that the doors are clear requires continual observation as the doors close. To minimize the potential for closing the doors on a passenger, observation techniques should address the platform area in front of the doors with the area extending out as far as possible from the side of the vehicle.

When the car side doors are under direct visual observation, a wide field-of-vision in front of the car doors can be observed in cases where no facility obstructions exist. The clear field-of-vision in front of the doors allows the operator to observe any passengers running in an attempt to board the train at the last minute. The time from an activation of the door-close

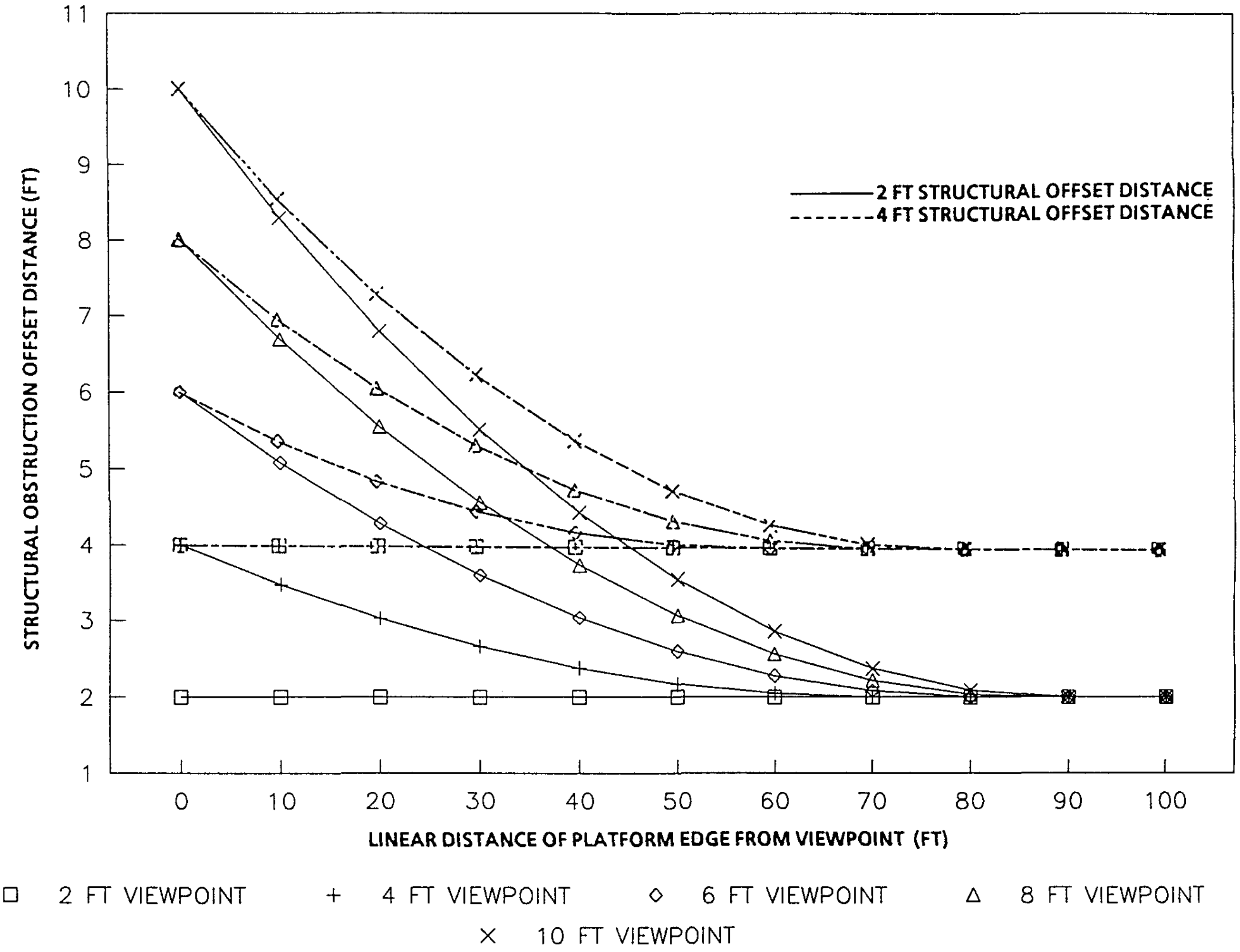


*Figure 7. Graphical representation of minimum allowable structural offset distances for 100-ft train for multiple viewpoint distances.*

button to the point where the door panels touch each other can range from 1 to 2 sec, depending on the operational characteristics of the door control and actuation systems. Where a chime is used to indicate the closing of the doors, this time can increase. The chimes generally last 1 sec and are followed directly by movement of the doors. During the generation of the chime and door closing process, the train crew member responsible for door control can override the closure process by activating the door-open control. Between the reaction time of the operator and the door control system, it will take approximately 1/2 sec for the doors to reverse their direction of travel. The doors can close approximately half the distance between the panels. Combining the reaction time and the door closure time, 1 sec will elapse before doors will come out of contact with a passenger. For this reason, the distance that the person operating the doors must see (offset observation zone) represents the distance a passenger will travel in 1 sec.

The optimal distance can be readily calculated as follows. The normal, full-stride running speed for the average human is approximately 6 mph. The average passenger will be traveling at a rate of approximately 50 percent of this speed or 3 mph. This reduction accounts for three factors: 1) acceleration from nearby platform entrances, 2) obstructions or passengers on the platform requiring avoidance, and 3) deceleration either in anticipation of boarding the train or of the doors closing before entering. Assuming a period of 1 sec from the point of physical activation of door control to actual door closure, the passenger has traveled:

$$\frac{3\ \text{mi}}{\text{hr}} \times \frac{\text{hr}}{3{,}600\ \text{sec}} \times \frac{5{,}280\ \text{ft}}{\text{mi}} \times 1\ \text{sec} = 4.4\ \text{ft}$$

This is a relatively large area of clear platform that is not always available in either underground or above-ground stations. Facility columns and platform entrances commonly restrict the viewing area of the operator. Additionally, entrances require special consideration in relation to car door observation, because passengers will enter the offset observation zone at a slightly higher speed because they are already in motion from the point of entrance onto the platform. The distance from such access points as stairs, escalators, and common waiting areas to the platform edge is generally less than 6 ft. Several stations were observed where this distance was less than 4 ft.

To account for the limitation in the operator's observation area where facility obstructions exist, devices should be installed to assist the operator in determining if the offset observation zone in front of all the doors is clear. These devices should be selected and installed to help enhance observation of platform access points as well as to fill in any blind spots because of obstructions relative to the observer's location.

## Facility Considerations

The ability to ensure that car side doors can be readily observed is primarily governed by the line of sight that the operator can observe, either directly or by using observation aids. During the site visits, the researchers observed hundreds of transit stations to develop an understanding of the operational and functional characteristics that affect observation procedures. Factors influencing the operator's ability to view the side doors were analyzed, classified, and documented as to their relative impact on the observation procedure. At several of the transit systems visited, certain stations had facility structures or platform configurations that restricted clear observation by an operator. For example, directional signs were placed close to a mirror, so that much of the mirror's viewing area was obscured. In general, observational requirements and facility considerations can and do vary from site to site. For unique circumstances, critical issues in the observational design of the stations can be addressed through careful analysis and evaluation of all applicable factors.

### *Platform Configuration*

The configuration of the platform edge in relation to the side of the train is one of two key elements that affect the operator's ability to observe the side doors of the train. The level of curvature often determines whether or not the operator needs observation aids to observe specific portions of the train. These portions are commonly toward the rear of the train, because the operator usually is located in the middle or toward the front of the train. Table 2 identifies the approximate number of stations where the platform edge is curved, for those transit systems that either were visited or that responded to the questionnaire. Of the 30 systems presented in the chart, 20 operate with platforms configured in a straight line. For the remaining 10 systems, the platforms are a combination of straight and curved.

### *Facility Obstructions*

The second key element that restricts overall observation by an operator arises from structures permanently located in the viewing area of the operator. The most common structures are building support columns, which are readily found in underground stations. These older stations, especially those located in metropolitan areas, often have support columns near the platform edge. Close spacing of these columns can create the effect of a wall at just a short distance from the operator's location.

For a straight platform, the operator's view of the platform beyond the "wall" is completely obscured. When the columns are near the platform edge (e.g., MTA-NYCT at 10 in.), the ability to observe passengers boarding the train is severely limited. For convex-curved platforms, the wall effect can also limit the operator's ability to directly observe the side doors at the far ends of the train, and columns along the platform edge may restrict the capability of aids to assist the operator in observing the side doors.

Other structures commonly found at many stations, especially those located above ground and exposed to weather, include passenger waiting areas. Some of the observed waiting areas, especially older designs, have solid walls. These structures and their relative location on the platform can obscure the viewing area of much of the platform.

For the development of new stations, or in major reconstruction programs, the use of columns should be minimized as much as possible; however, a cost/benefits trade-off may necessitate some form of column requirement on the station platform.

Table 2 categorizes the degree of structure obstruction experienced at some of the most severely obstructed stations of the particular transit system. The ranking is subjective and generally represents only a few of the stations of the transit system. Because of obstructions at these stations, operators must pay additional attention to ensure that no passenger enters the train as the doors are closing. Four transit systems were classified with a medium level of obstruction.

The highest level of observation is clearly obtained when there are no obstructions on the platform that hinder operator ability to observe along the side of the cars or the area in front of the doors at a distance generally of 10 to 15 ft. These are clearly optimum requirements and are commonly not obtainable during new construction or in station refurbishment or replacement.

External factors, such as the need for columns or other support or elevator or escalator installation next to the platform edge, can limit visibility.

For light rail systems, which can operate at street level, the location and design of installed structures and obstructions must be carefully reviewed. Addition of trees, signs, and street lighting fixtures, while often pleasing to the public, can affect observation, especially as the trees grow larger; such additions must be carefully evaluated during design.

*Passenger Elevators.* In the design of new stations and the retrofit of older units with elevators, the location and the material design of elevators must be carefully reviewed to limit the potential obstruction of an operator's view of the platform. As part of improved accessibility of stations for the physically impaired, several systems are installing new elevators. Although these units should be as far from the platform edge as possible, the limitations on design and the physical characteris-

TABLE 2 **Summary of station and platform configurations**

| Transit System | Qty Stations | Subway/ Grade/ Elevated (percent) | Platform Straight/ Curve/ Mix | Concave/ Convex/ Both | Stations Concave (Percent) | Degree of Platform Obstruction | Platform Edge Identification |
|---|---|---|---|---|---|---|---|
| BART | 34 | 33/33/33 | STR | - | - | Minimal | Yellow-Detect |
| LA-HR | 19 | 5/95/0 | STR | - | - | Minimal | Yellow-Detect |
| LA-LR | 5 | 100/0/0 | STR | - | - | Minimal | Yellow-Detect |
| CTA | 142 | 25/60/15 | MIX | Concave | 2 | Minimal | Yellow Stripe |
| GCRTA-LR | 29 | 5/95/0 | MIX | Both | 5 | Minimal | Stripe/Det |
| GCRTA-HR | 18 | 17/83/0 | STR | - | - | Minimal | Stripe/Det |
| MARTA | 33 | 48/48/4 | STR | - | - | Minimal | Yellow Stripe |
| MBTA | 50 | 33/63/4 | MIX | Both | Minimal | Minimal | Stripe |
| Toronto-Scar | 6 | 0/0/100 | STR | - | - | Minimal | Stripe |
| Toronto-HR | 60 | 70/30/0 | STR | - | - | Minimal | Stripe |
| MTA-NYCT | 469 | 59/8/33 | MIX | Both | 20 | Med - 10" min | Yel Str/Det |
| PATH | 13 | 65/20/15 | MIX | Both | 5 | Medium | Yel Str/Det |
| BC Transit | 17 | 20/20/60 | STR | - | - | Minimal | Yel Str/Det |
| Jacksonville | 3 | 0/0/100 | STR | - | - | None | Yellow-Detect |
| Miami-HR | 21 | 0/0/100 | STR | - | - | None | Yellow-Detect |
| Miami-PM | 9 | 0/0/100 | STR | - | - | None | Yellow Stripe |
| WMATA | 70 | 50/30/20 | MIX | Both | 4 | Minimal | Flashing Lights |
| Baltimore-LR | 24 | 0/100/0 | STR | - | - | None | Stripe |
| Baltimore-HR | 12 | 50/25/25 | STR | - | - | None | Stripe |
| SEPTA-Orange | 26 | 95/5/0 | STR | - | - | Medium | Yel Str/Det |
| SEPTA-Blue | 36 | 40/0/60 | STR | - | - | Medium | Yel Str/Det |
| PATCO | 13 | 40/40/20 | MIX | Concave | 10 | Minimal | Stripe |
| Edmonton | 10 | 38/62/0 | STR | - | - | None | Stripe |
| Calgary | 30 | 10/80/10 | MIX | Both | 10 | Minimal | Yellow Stripe |
| Metro-North | 118 | 2/98/0 | STR | - | - | Minimal | Yellow Stripe |
| Sacramento | 28 | 0/100/0 | MIX | Convex | 5 | None | Yellow Dots |
| PAT | 15 | 10/85/5 | STR | - | - | None | Stripe |
| SF MUNI | 9+ | 29/71/0 | MIX | Concave | 10 | None | Yellow-Detect |
| LIRR | 134 | 3/75/22 | MIX | Both | 4 | Minimal | Yellow Stripe |
| Montreal | 65 | 100/0/0 | STR | - | - | None | Yellow Stripe |

tics of the station often prevent this. To limit the potential reduction in viewing area, the installation of an elevator with clear panels in the fixed structure and the elevator car itself can assist the operator to observe through the structure for passenger egress and ingress.

*Escalators and Stairs.* Many subway and elevated stations use stairs or escalators for passenger access; these structures are, in some cases, near the platform edge. For elevated platforms, the obstructive effect of stairs and escalators on observation can be limited by designing surrounding walls that are no more than 3 ft high. For platforms where passenger access is provided from upper levels, the structure plays a greater role in restricting observation by an operator. For designs of new stations and for major reconstruction of existing platforms, the access location should be carefully considered to minimize the obstruction potential.

Where physical limitations prevent adequate distance of the access point from the platform, consideration should be made to accommodate direct observation of the stairs by the train crew member responsible for door operations. For example, escalators and stairs should deposit passengers on the platform so that they will face the train crew's observation location. In this way, passengers running to catch trains will be seen when they reach the platform, thereby allowing the train crews to react accordingly.

### *Lighting*

Illumination of the platform edge is important in the clear observation of car side doors, although to a lesser extent than platform configuration and facility obstructions. Adequate, consistent levels of illumination are required to provide a clear image and definition to the operator of the passenger boarding process. Inadequate light levels make it difficult for an operator to determine the status of passengers boarding, especially when the observation is conducted over a long distance.

Several transit systems have established minimum light levels for their operations. Among those providing specifics, Port Authority Transit (PAT) in Pennsylvania had the lowest required minimum level—5 fc. Alternately, Montreal requires a minimum level of 27 fc in its stations. Some systems require different levels of illumination for different station scenarios. Calgary requires higher illumination levels at its downtown stations versus its outlying stations. MTA-NYCT requires slightly higher illumination levels for its covered stations as compared to its exposed platforms.

Major variances of light levels along the platform edge and at the ends of a platform also affect an operator's observation capability. This is especially true for stations affected by variances in sunlight.

For platforms directly exposed to sunlight, the changes in light level caused by shadows of the facility structure can make it difficult for an operator to distinguish among images on the platform. This is especially true when an overhead protective structure only covers part of the platform, requiring the operator to view the side of the car under varying levels of illumination.

Several stations were also observed where the entire station is covered, but the ends of the station are open to the elements. Under these conditions, bright sunshine can increase an operator's ability to view the end of the train; however, this can also be a detriment, because the brightness relative to the darkness of the platform may limit the ability to distinguish closer images.

Another factor associated with illumination that must be considered in observation practices is the effect that reflected light or glare from the sun may have on an operator's viewing area. Glare from highly reflective surfaces, such as glass-faced buildings or even the side of the train, can prevent the operator from looking in a particular direction because of the severity of the light. This blinding may restrict the operator's view for the entire side of the train or only for a small portion. In either case, the potential for this must be evaluated and addressed so as to minimize any effect.

In summary, providing adequate, consistent light levels is important for the clear observation of car side doors, whether for underground, enclosed stations or at exposed, elevated stations. This is true not only for direct observation by the operator but when using various visual observation aids. As discussed in the section on usage guidelines for CCTV systems, adequate, consistent light levels are also required to allow the camera to detect and the monitor to display the images on the platform.

## EXISTING OBSERVATION AIDS

During the transit property site visits and through the questionnaire responses, the researchers identified mirrors and CCTV as existing rail car side-door observation aids. In addition, the researchers identified two transit properties that use platform gates and barriers to enhance passenger safety. Although these are not observation aids in the strictest sense, they address the general issue of platform safety and, as a result, are germane to the research. The following sections discuss the use of these types of aids. Part II of this report includes full details on the use of mirror and CCTV-based observation aids for the individual transit properties visited during the project.

### Mirrors

Of all current observation aids, mirrors have found the widest usage in the transit industry. This is because of their low procurement cost, ease of installation, and low life-cycle maintenance costs. During the site visits, mirrors were seen in use on 11 of the 17 properties visited. Case studies relative to mirror usage for each of these 11 properties are provided in Part II of this report. In the responses to the transit property questionnaire, an additional five North American light rail systems (including Edmonton, Calgary, Sacramento, PA Transit, and San Francisco Municipal) were identified as users of mirrors as observation aids. Also, the Moscow Metropolitena in Russia and the Metro de Madrid in Spain reported mirror use in their questionnaire responses. The balance of this section will provide details on mirror use for those properties visited as part of the research program.

In general, the properties using mirrors were consistent in how mirrors were used for door observation. There was little variance in use from system to system and little that could be classified as unique. Mirror use was observed in both heavy and light rail operations with all light rail vehicles observed being equipped with some type of mirrors. For light rail vehicles, the mirrors are generally the sole method employed to view the doors.

In very few cases did an operator of a light rail vehicle make direct visual observation of the doors. For heavy rail vehicles, the mirrors are employed where a conductor or train operator needs to see around a platform curve or an obstruction. Generally, the train operator uses the images provided by the mirrors to supplement what he or she can see by direct visual observation.

Most of the mirrors in use have a convex face that enables the user to see around curves. These mirrors tend to distort the image, with the center of the image appearing the largest. Moving from the center of the mirror toward the edges, the image on convex mirrors gets progressively smaller. Even at its largest point, the image seen in the convex mirror will be about one-half the size of what would be seen with the naked eye. Where straight line observations are to be made, as is the case with most light rail vehicles, flat mirrors are used.

Flat mirrors do not distort the image, do exhibit images of consistent size across the face of the mirror, and do not shrink the image relative to what is seen by the naked eye. These characteristics were observed during the demonstration of the mirrors at PATH where a flat mirror was installed next to a convex mirror for comparison purposes.

The researchers found that mirror use has achieved a high degree of acceptance with nearly all train crews; however, use is affected by mirror characteristics and maintenance. In a few cases, mirrors were observed to have been vandalized—faces were cracked or mirror mounts were bent so that the mirrors were unusable. In other cases, the mirrors appeared to be dirty, which reduced their usefulness. These conditions were found at surface and subway stations equally.

### Closed-Circuit Television

Although CCTV-based observation aids are used in North American transit properties, their use is limited. European and

Far East transit properties make much broader use of CCTV. During the site visits, CCTV-based observation aids were seen in use on 4 of the 17 properties visited. These included CTA in Chicago, MTA-NYCT in New York, PATCO in New Jersey, and TTC in Toronto. Other properties (e.g., WMATA in Washington, DC, and MARTA in Atlanta) have platform CCTV cameras; however, these systems do not present the video to the train crews locally in the station. On these systems, the video is routed to a station office or to a command center. With the exception of MTA-NYCT, the use of CCTV was very limited. For example, TTC is only using CCTV on a trial basis and has only two stations and six rail cars equipped with CCTV provisions.

In addition to the four identified users, SEPTA in Philadelphia has indicated that CCTV will be employed on the new rail cars being built for the Market-Frankford line. These new vehicles will be designed for single-person operation from the onset (rather than the current two-person crews), and cabmounted video monitors will be used to allow the train operator to verify that the train doors are clear. This is ground breaking—it represents the first use of CCTV as the primary means of door observation in North America.

In addition to these five North American users, Teito Rapid Transit (Tokyo), the Transportation Bureau of Tokyo Metropolitan Government, Moscow Metropolitena, Metro de Madrid, and Hong Kong's Mass Transit Railway Corporation were identified as users of CCTV from the questionnaire responses.

Where CCTV is being employed in North America, it is used as the sole means of observation in the stations where it is installed, i.e., the train operator is not required to look at anything but the monitors to see the train doors. The exception to this is CTA in Chicago, where CCTV is used in a single location to provide an image of part of the train, which is out of the conductor's field-of-vision.

For the CTA application of CCTV, a single camera is generally used and a platform-mounted monitor provides a fullscreen image of the camera video. In the other three cases, a sufficient number of cameras is used to provide a view of the entire side of the rail car and the adjacent platform edge. These three systems employ platform-mounted monitors positioned so that they will be visible to the person responsible for door control.

In the case of MTA-NYCT, multiple monitors are provided along selected platforms to support multiple stopping locations for trains of varying length. In this case, the same cameras are employed for each set of monitors. All CCTV installations observed employed monochrome (black and white) images and, excluding CTA, used split-screen images to provide the views of two cameras on a single monitor. Generally, the CCTV observation aids enjoyed a high degree of acceptance, with nearly all train crews observed employing them. All of the CCTV systems observed were in good working order and appeared to be properly maintained.

In all cases, the CCTV systems were protected against vandalism through the use of protective enclosures for all system components, including the monitors and cameras. None of the CCTV systems seen exhibited the effects of vandalism.

*Figure 8. Platform gates and barriers on Disney World monorail system.*

## Platform Gates and Doors

In several locations visited, gates and doors are used to separate the passengers and the trackbed area. Although these gates and doors are not observation aids in the strictest sense, they help separate the passengers and trackbed when the train is entering and leaving the station.

Platform gates were observed at the Skyway System in Jacksonville, Florida, and on the Monorail at Walt Disney World. Figure 8 illustrates the gate arrangement in one of the stations at Disney World. Platform doors were seen in use on the people-mover systems at the airports in Orlando, Atlanta, and Pittsburgh. In addition, Teito Rapid Transit in Japan indicated (via a response to the questionnaire) that they use platform doors in one of their stations.

In the case of the Disney World Monorail, the gates keep passengers away from the platform edge during train arrival and departure. These gates provide an additional benefit by defining an observation zone along the side of the vehicle. However, the monorail has station dwell times of 2 to 3 min, and the door controls are on the outside of the vehicle, aft of the cab. Because the train crew member must leave the cab to operate the doors, observation of the doors becomes considerably easier.

Like the Metromover system in Miami and the SkyTrain system in Vancouver, Jacksonville's Skyway system is fully automatic. The vehicles are unstaffed and there is no cab or other provision for manual operation.

*Figure 9. Jacksonville Skyway platform gates.*

A unique aspect of Jacksonville's Skyway is its system of platform gates and edge warnings. Each station platform has several gates and openings that match the door layouts of the vehicles. This approach prevents incursions by all but determined individuals while ensuring ease of passenger movement.

Because the trains stop at the same location in the station (±14 in.), the opening in the gates generally matches the vehicle door openings. Figure 9 illustrates one such set of gates. These gates cover the entire length of the platform to prevent passenger incursions into the trackbed. Openings in the gates are guarded by a pair of photoeyes, with visual references provided by warning signs, stripes, and colored tactiles. The first set of photoeyes is approximately 12 in. from the platform edge and causes a warning beacon to illuminate and a loud alarm to sound.

When the photoeyes are cleared, the beacon and alarm turn off after a few sec. The second set of photoeyes are approximately 3 in. from the platform edge and cause an alarm to be sent to the control center and vehicle power to be removed in the blocks in and around the station. These alarms must be cleared by the control center operator. Although such a system could be used for a staffed transit system, it is most suitable for automated systems.

The SkyTrain system in Vancouver also employs sensors on the platform and in the trackbed. This system is geared to detect right-of-way incursions and is not equipped to detect passengers too close to the edge of the platform or passengers trapped between the rail car doors.

## CONCEPTUAL OBSERVATION AIDS

As stated, the research team envisions observation aids falling into two general classes—aids that support and enhance the range of human vision and aids that employ machine vision techniques. Aids used to enhance human vision include mirrors and CCTV-based systems. In these cases, a train operator or conductor views an image of the sides of the rail car as presented by the aid. The train operator must then interpret these images and evaluate the results against the transit property's operating rules to decide if the doors are clear.

Conversely, a machine-vision-based system will provide an assessment of the door situation independent of human interaction. These systems will use some form of sensing technology to view the doors. The sensor outputs will be used by a microprocessor-based system controller to determine the status of the doors on the basis of an observation algorithm and safety rules. The safety rules become the metric used to assess door safety and are generally constant, with small variations to reflect transit property operating rules, equipment configurations, and facility characteristics. The algorithm used to process sensor data is dictated by the sensor technology.

The following paragraphs address the potential for advancements in existing observation aids and development of new classes of observation aids based on existing and emerging technologies.

## Conceptual Mirror-Based Observation Aids

Mirrors are passive devices that operate according to one of the basic rules of physics. Because they are simple tools, the most significant potential for advancements in mirrors lies in enhancing and structuring their application and enhancing their resistance to vandalism. Discussion of these two aspects of mirror use are provided in Chapter 4 of this report, under the heading of Observation Aid Usage Guidelines.

## Conceptual CCTV-Based Observation Aids

CCTV-based observation aids are defined in terms of their general system architecture (which defines the functional methodology) and the individual components and subsystems (which implement this architecture). The potential for conceptual CCTV-based observation aids depends on the development of advanced architectures for the systems and the use of system components incorporating state-of-the-art technology.

The current systems studied by the researchers are fairly basic; therefore, there is considerable potential for improvement. The following paragraphs discuss the architecture and components of CCTV-based observation aids and provide details on how they can be enhanced.

### *Conceptual CCTV-Based Observation Aid Architecture*

The basic concept in the design of CCTV-based observation aids is that a clear image of the side of the rail car must be presented to the train crew. Because the time for observation is brief and there is considerable platform activity during this period, this image must be presented to the train crew in real time. Having established these underlying operational principles, it is possible to assess how the architecture of CCTV-based observation aids can be enhanced to increase their usability and suitability to their assigned task.

The most basic advancement that could be made in the architecture of CCTV-based observation aids is to use color images. Color images provide greater contrast between people and objects, such as the rail car and platform features. For example, the warning stripe at the edge of most station platforms is yellow. This color contrasts with the concrete gray of the platform and the silver of most rail cars. Persons or objects crossing the stripe can be easily seen. During the CCTV-based observation aid demonstration performed at PATH, a color system was used and this contrast difference was illustrated. In addition, several of the PATH train crews that viewed the images provided by the demonstration system commented on the benefits of the color images.

Comments made by transit property personnel during the site visits indicated that color video was not used because of cost considerations; however, the cost of color equipment is only slightly higher than monochrome equipment. Generally, this cost is about 25 percent greater for a color camera or monitor than for an equivalent monochrome unit. The following paragraphs provide information on other advanced CCTV-based observation aid strategies.

*Vehicle-Mounted CCTV.* All of the CCTV-based observation aids used to date have station- or platform-mounted cameras. It is possible to employ train-mounted cameras that could essentially make the observation aids self-contained on the rail vehicle. This alternative is supported by the current range of miniature CCTV cameras designed for security applications. Some of these cameras are cylindrical in shape and have a diameter of approximately 2 in. and a length less than 6 in. Such a camera could be placed in a weatherproof enclosure and mounted on the side of a rail car. Located at the head of the rail car, this camera would provide an image of the plane of the side of the rail car. Figure 10 shows the location of the camera with references to aid in defining the vertical field-of-vision requirements.

The horizontal field-of-vision is not an overly significant concern because this type of system will sight along the side of the car and only a small horizontal field-of-vision is required. In this illustration, the distance between the camera and the set of doors closest to the camera determines the field-of-vision. The closer this set of doors is to the camera, the wider the field-of-vision that is required. The field-of-vision is defined mathematically as:

$$\text{Field-of-vision (Degrees)} = \text{Arctan}\ (H/D)$$

In such a system, the video from individual cameras could be routed to the cab through trainlines and displayed on a monitor. Figure 11 is a block diagram illustrating a potential architecture for such a system.

Through the use of video signal switching, the system could be configured so that any rail car equipped with the appropriate hardware could serve as the lead car of the train. In addition, the video could be displayed on the monitor in any cab on the train. The cab monitors could be used to display a quad image that would show as many as four cars (as shown in the block diagram of Figure 11) or could use split-screen images for shorter trains or switched quad images for longer trains.

A simplified version of this system could also be applied to light rail vehicles, which are generally shorter than heavy rail cars. A system for a light rail vehicle could use either a single or dual cameras and would not require trainlining of video images.

Because the electromagnetic environment for trainlines is

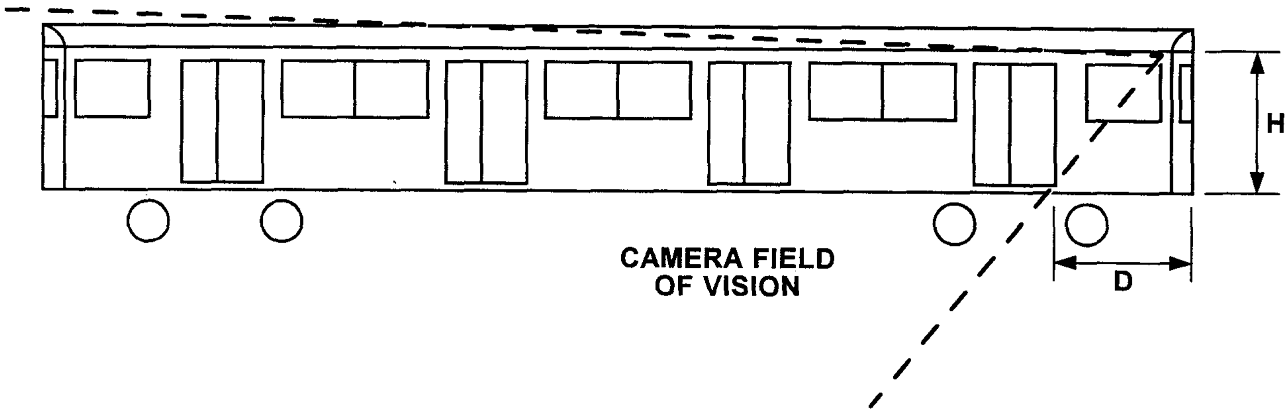


*Figure 10. Vehicle-mounted CCTV camera field-of-vision.*

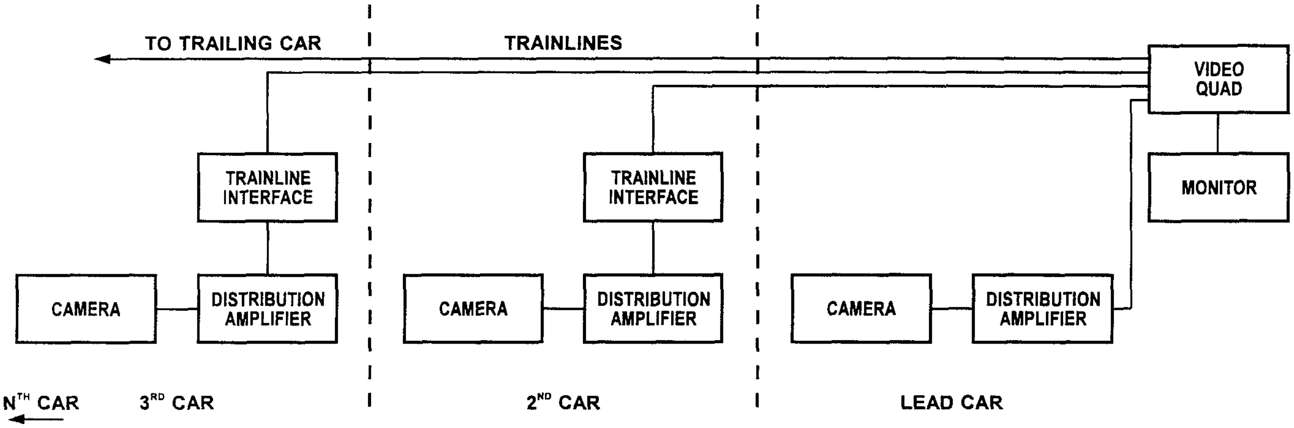


*Figure 11. Vehicle-mounted CCTV system block diagram.*

fairly noisy, these signals would need buffering using line amplifiers as shown in Figure 11. As an alternative, a fiber-optic system could be employed to route all train video signals to the active cab via a single fiber. Because of the broad bandwidth of fiber-optic cable, a fiber backbone could also incorporate vehicle interior communications and vehicle health monitoring.

An offshoot of this approach could be a CCTV-based replacement for the mirrors used on light rail vehicles. With such a system, the cameras could be positioned to provide an optimal view of the doors and would not require adjustment by individual train operators because their view would be provided by the cab-mounted video monitor. In developing such a system, it must be considered that some light rail systems operate on city streets, sharing them with vehicular traffic. In this case, the train operator would also use the CCTV to avoid collisions. For this reason, some form of switching should be employed to provide the train operator with an optimal view. Such a system could have four cameras, with one at each corner of the vehicle. The fields-of-vision of these cameras would be oriented toward the center of the vehicle.

With the vehicle in motion, the cameras adjacent to the active cab would be displayed on the monitor in split-screen format to emulate the rear view mirrors. When the vehicle stops and the doors are opened, the monitor would display the video from those cameras on the side of the vehicle with the doors open. This switching could be accomplished automatically using signals from the door control system. With the doors closed, the display would revert to the rear-view-mirror mode.

*Enhanced Platform and Vehicle CCTV.* Although several CCTV systems are in operation as reported above, these fairly basic systems do not exploit the full range of CCTV technology available. In these systems, image representation, image delivery, and display technology could be improved. While in some cases these improvements could be realized through the use of state-of-the-art components, most would require changes to the system architecture. In addition, some of the changes would be interrelated and would have to be implemented in combination to be effective. The following paragraphs discuss the potential for enhancements in these areas and describe the relationships between them and how each relates to the overall system architecture.

### *Image Representation*

In the systems seen to date, the image presented to the train operator is either full-screen or split-screen. For MTA-NYCT, multiple monitors are sometimes necessary to provide all the required images to the train crew; this necessitates additional hardware and installation and requires the train crew to scan the images provided on multiple monitors. This last fact is of particular concern because the situation presented by one monitor may change while the train crew member is viewing the other. With this in mind, it is desirable to provide train crews with all required images on a single monitor.

One way to do this is to use a quad-image combiner. The combiner allows the images from up to four cameras to be merged into a single image by taking the four images and placing each in a quadrant of the monitor defined by vertical and horizontal dividing lines (see Figure 12). Quad-image combiners operate by digitizing the individual images.

Split-screen devices simply switch between the camera inputs at the middle of a horizontal interval (video line). If the two video sources are not synchronized, the combined image will be unstable; therefore, the two cameras must have common synchronization routed through a distribution amplifier to ensure signal integrity. This costs more because of hardware and installation cabling. Quad-image combiners cost roughly three times that of a screen splitter; however, the quad-image combiner will allow the elimination of a monitor, both screen splitters, and two distribution amplifiers. As a result, the quadimage combiner approach will probably be cheaper than the dual split-screen approach.

Although some quad-image combiners do not operate in a real-time mode and provide images that look like freeze frames with a 1- to 2-sec update rate, newer units can provide realtime images in color or black and white.

One potential drawback of such a system is that images are compressed, i.e., a full-screen monitor image is presented in a space equal to one-fourth of the total screen area. This problem can be solved by using larger monitors or by moving the monitor closer to the person who will view it.

### *Image Delivery*

Excluding TTC, existing CCTV systems employ platformmounted monitors. This is the cheapest alternative for CCTV-based door observation aids, but it has several operational limitations. In these systems, the monitors are mounted on the platform at a point corresponding to fixed train stopping points. As a result, monitors can be used only for a single, fixedlength train. In selected cases, such as at MTA-NYCT, multiple monitors have been installed to allow operators of trains of different lengths to use the CCTV installation.

Another drawback of platform monitors is that variation in train stopping points can cause the CCTV monitors to be out of the usable viewing range of the train crew. This was observed during the CCTV demonstration at PATH. While this is not as much of a problem for trains with automatic controls—because of their stopping accuracy (generally less than ±2 ft)—trains under manual control could experience problems because of their average stopping accuracy of ±4 ft.

The research team observed that, in some cases, trains missing their stopping mark by as little as 3 ft can obscure the train crew's view of the monitor. When these trains miss their marks, the angle between the viewer's position and the face of the monitor becomes increasingly obtuse, which limits the train crew's ability to use the monitor image reliably.

The obvious solution to this problem is to move the monitor relative to the train crew. The best way to do this is to use train-mounted monitors like those employed at TTC. These monitors are mounted in the cab so they can be viewed regardless of the train's stopping position. An additional benefit is that the train crew is physically closer to the monitor, which allows them to better assess the scene presented.

The technical challenge presented by this situation lies in the means of image delivery to the train. Because hardwired interconnection, such as that is used in platform-based systems, is impossible, a different means of transmission must be employed. Multiple solutions can be employed to transmit video images from the platform to a train. These solutions include various forms of RF and infrared transmission. The following paragraphs provide details on each of these two approaches.

*RF-Based Transmissions.* Various RF transmission schemes can be used to transmit real-time CCTV images. These include near-and far-field transmission systems. Near-field transmission systems are defined as those systems that operate with very low radiated power and, as a result, require the transmit and receive antennas to be close together. An example of a system based on near-field transmission is that used in Hamburg, Germany.

This system employs receive antennas mounted under the car body and a leaky coaxial cable located in the trackbed. Most train stations have two tracks with a platform or a single side of an island platform serving each track. As a result, the video images that must be provided to the train depend on the track and platform being used.

A benefit of near-field transmission systems is that they isolate video signals for two trains operating on different tracks within the same station without using dual frequencies. Generally, these systems operate at around 50.5 MHz with extremely low levels of radiated power. Such a system could not be used in North America because 50.5 MHz is in a band allocated for use by 6-m amateur radio operators.

The leaky coaxial cable used in these near-field transmission systems is extremely inefficient; therefore, the transmitter must produce a much higher level of power than that required for a conventional transmission system. In addition, because the system components are located in the trackbed areas and on the underbody of the rail car, they are highly susceptible to electromagnetic and radio frequency interference (EMI/RFI) generated by the propulsion systems of these vehicles.

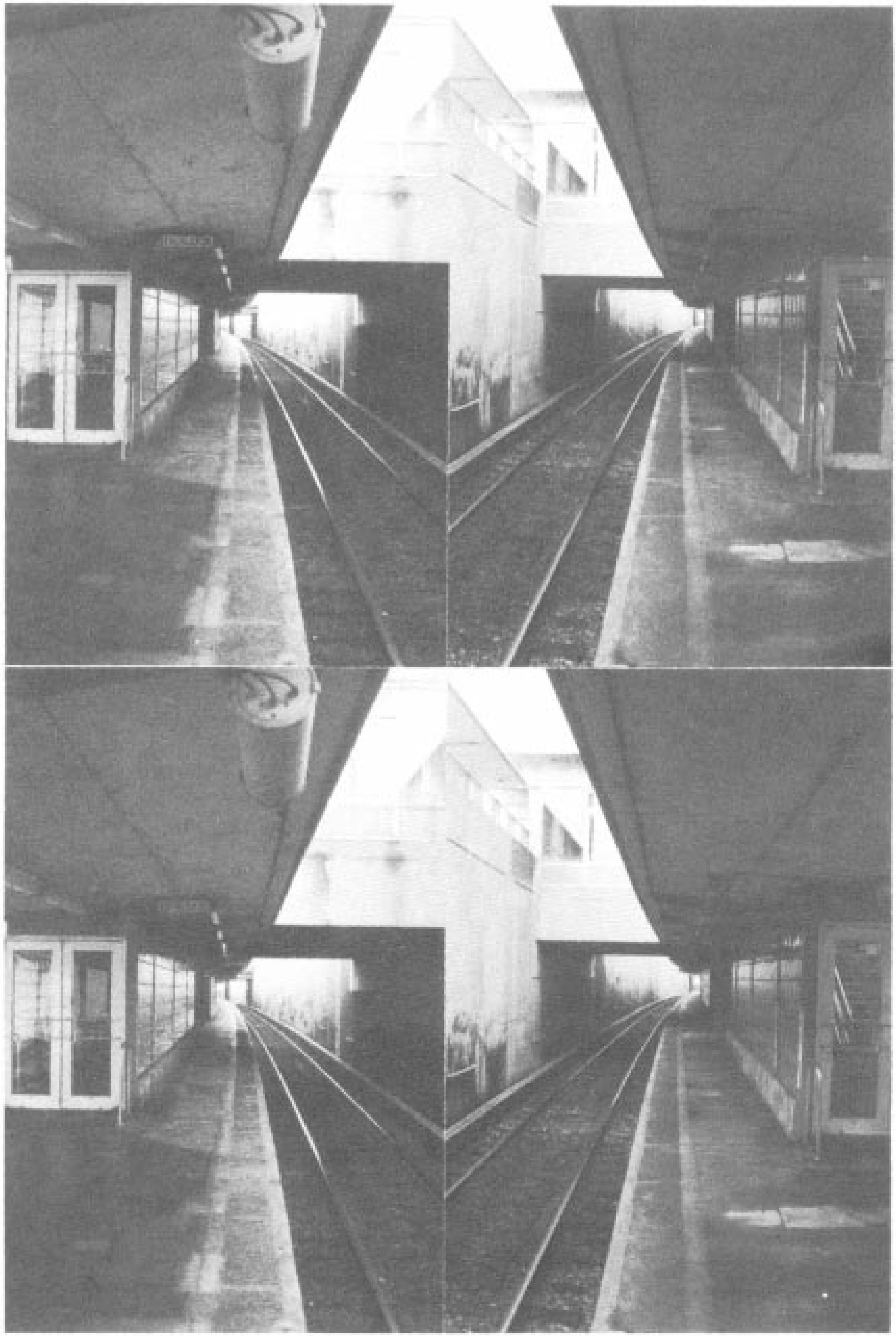


*Figure 12. Quad image video presentation.*

The antennas in near-field systems must be spaced no more than 8 in. apart. For this reason, the antennas must be mounted in the trackbed close to the height of the top of the rail. In this position, the antennas are very susceptible to damage by foreign objects. Simple objects discarded in the trackbed can significantly damage the receive antenna and render the system unusable. In addition, the zone in which the vehicle will receive video is determined by the location of the leaky coaxial cable. If the cable is not run for the entire length of the platform, this will restrict operations. For example, temporary relocation of the train stop location will make the system inoperable.

The procurement cost of a near-field transmission system is also higher. The leaky coaxial cable costs approximately three times that of standard RG-59 coaxial cable per foot. Trackbed installation is expensive because of the trenching required to route the cable from the platform to the trackbed and because of the cost of fastening the cable to the rail ties securely. Such cables are also subject to lateral and vertical displacement caused by the weight loadings induced by passing rail vehicles.

Far-field RF transmission systems are designed to operate with nominal levels of output power, thereby allowing greater antenna separation distances. These systems can be classified into licensed and unlicensed systems. Licensed systems are those that require a Federal Communications Commission (FCC) site license to operate; this license covers a geographic location and ensures that the user will be the sole licensee of a specific frequency in a geographic area. This guarantees the user that there will be no outside interference with transmissions. Generally, the licensing process is not difficult, and equipment manufacturers will assist their customers in this process.

Most licenses can be obtained in 6 months or less. Licensed systems suitable for the application to CCTV observation aids include those operating at frequencies in the 2.3 to 2.5 GHz bands. Unlicensed systems do not require FCC operating approval and are suitable for the door observation application. The research team worked with a 902 to 928 MHz unlicensed system to assess its susceptibility to outside interference. Although this frequency band is shared with other consumer electronics, no perceptible interference was observed.

The researchers conducted trials of an unlicensed system in both urban and general suburban environments. To stress the equipment, these tests positioned the receiver and transmit antennas at the extremes of their coverage ranges. In all cases, the image provided was usable and exhibited no distortion or interference from outside sources. The equipment tested employed circular polarized microstrip antennas with a transmit beam width of 160°. This broad beam width could be used to provide images to the train before entering the station, while in the station, and after leaving the station (via antenna backlobes).

A transmission system operating at 905 MHz was tested at PATH as part of the CCTV demonstration. This system operated at low power levels and experienced very little interference from train equipment. The only interference experienced was when the train started moving. This interference manifested itself as minor snow, which could be seen on the video monitor. This interference probably resulted from transient noise generated when the traction motors started. It is possible that, if the transmitter were operating at higher power—as is allowed by FCC regulations — this interference would have been eliminated.

As stated above, licensed systems guarantee the user that interference from outside sources in the same frequency band will not be experienced. This class of system includes those operating in the 2.3 to 2.5 GHz and 21.8 to 23.2 GHz bands. In reviewing the higher frequency systems (i.e., 21.8 to 23.2 GHz), it was determined that the antennas in these systems have a 3 dB beam width of 3.8°. This beam width is too narrow to develop a practical application for a door surveillance system because minor curvatures in the track can put the antennas out of alignment. The prospective user must assess the electromagnetic environment in which the system will be used in order to select the appropriate frequency range.

*Infrared-Based Transmission.* Infrared-based transmission is another approach to unlicensed transmission of video images. These systems consist of a transmitter and receiver with the transmitter using a laser diode to produce frequency-modulated infrared energy. They transmit with a power level of 10mW in the 800 to 850 nm wavelength range. The systems reviewed had operating ranges up to 2 mi. Although these systems are not in use in North America, in the United Kingdom, they are used as part of CCTV-based observation aids.

A potential problem with an infrared transmission system is that the beam of infrared energy it uses is very narrow. The transmitter has a maximum beamwidth of 20° at a point approximately 120 ft from the transmitter optics. This beamwidth decreases as the distance from the optics increases. At a distance of 350 ft, the beamwidth is about 5°. In addition, the receiver also has a beamwidth specification, which is generally on the order of 5°.

Taken together, the beamwidth specifications make alignment of the transmitter and receiver optics very critical. Because of these alignment constraints, the researchers think that such a system is most suited to underground applications where the transmitter can be mounted on the ceiling in a tunnel and the receiver can be mounted on the top of the rail vehicle to maintain alignment. Although problematic, this could help make the system immune to interference from other sources of infrared energy—interference would have to be directed at the receiver for the interference to be a problem. In addition, the beamwidth will be beneficial where multiple tracks and platforms are in use in the same station and specific images must be routed to the train. The researchers also think that an infrared-based system would be susceptible to problems caused by fog or other precipitation. Atmospheric water vapor will tend to disperse the light beam, thereby reducing the amount of energy reaching the receiver.

### *Display Technology*

In designing rail cars, the goal is to provide the optimum space for carrying passengers; therefore, areas such as equip-

*Figure 13. TTC cab monitor presentation.*

ment space and the operator's/conductor's cab on rail vehicles are reduced to the smallest practical size. As a result, it is difficult to mount additional equipment in the cab. Video monitors pose a particular problem because of the depth associated with the cathode ray tubes (CRTs) around which they are built. This is particularly true for existing systems where the monitor installation is a retrofit. Designers of new rail cars can design other elements of the cab around the monitor installation.

As described previously and illustrated in Figure 13, TTC in Toronto has installed monitors with 9-in.-diagonal screens in the cabs of a few of its rail cars. These monitors were installed in the upper right corner of the cab with the screen slightly angled toward the train operator's position in the center of the cab. The researchers observed that the screen was located so as to be viewed under normal operating conditions. TTC has some concern that the train operators will hit their heads on the mounting brackets, as evidenced by the warning stripes placed at the front edge of the brackets.

Toronto's monitor installation was facilitated because TTC vehicles have a total cab depth in excess of 52 in. (i.e., window to rear wall), which makes them among the largest seen during the site visits. Most cabs are considerably shallower and mounting a conventional CCTV monitor is problematic. In general, a 9-in.-diagonal, CRT-based color monitor requires a mounting depth of 12.5 in., including room for rear connectors. Black and white monitors are only slightly smaller (i.e., nominal 12.1 in. depth for a 9-in.-diagonal monitor). Such depths are characteristic of CRTs, and little can be done with current technology to reduce the depth. Smaller monitors, such as 5-or 6-in.-diagonal screens, could be employed to reduce the depth, but the image begins to compress and detail will be lost.

A potential solution to this problem is the use of color, flat-panel liquid crystal displays (LCDs). These displays were first developed for the laptop personal computer market and are beginning to see use in consumer video products. Although they are not yet available in large quantities, it is expected that they will see widespread use by 1997. In addition, LCDs have been used in avionic displays on commercial and military aircraft. It is possible to produce a complete 10-in.-diagonal, flat-panel display with a total package depth of less than 5 in. These flat-panel displays are active-matrix LCDs that incorporate amorphous, silicon, thin-film transistors at each addressable dot. Advanced versions of these devices are constructed using glass sandwich encapsulization, which provides resistance to high humidity and to mechanical shock and vibration such as may be encountered in the mass transit operational environment. Illumination of LCDs is provided by high-intensity backlights. Features allowing dimming of up to 2,000:1 allow use of these displays under ambient light conditions varying from night to full sunlight. LCDs may fail to operate properly at low temperatures; however, a heater may be used to extend the operating range of the unit.

### *Machine Vision*

CCTV has been used to perform automated product inspection in manufacturing. In such systems, the image of a product on a manufacturing line is automatically compared to that of a metric (i.e., an image of a product known to be acceptable) to determine if there are differences. Units differing from the metric are rejected.

Machine vision requires that the image of a scene or object be captured and processed to allow comparison to the metric. This process requires computing resources, including devices known as frame grabbers, which capture video images by sampling them at a given time and storing them. Although machine vision could be applied to door observation aids, aspects of its use make it unacceptable. The most significant aspect is that machine vision cannot be performed in real time. Images of the door area would have to be captured and processed to account for scene changes arising from passengers running to enter closing doors and other operational factors. Although high-speed computers could perform this operation in near-real time, the cost of such systems would be prohibitive.

With the rise in multi-media computing that incorporates video image manipulation and processing, it is anticipated that the cost associated with the hardware and software will decline in the future, making machine vision a more cost-effective option. On the basis of current technological trends, it is anticipated that this will occur in 5 to 7 years (i.e., circa 2000). The following paragraphs briefly describe the basics of machine vision image processing in the context of door observation.

Machine vision systems can perform various forms of image enhancement and comparison. Most of these operations are pixel based. Pixels are the small units of video that constitute a total image. A standard video graphics adapter (VGA) computer video image consists of a matrix of pixels 1024 wide by 768 high (i.e., 786,432 total). Pixel manipulation techniques can be classified as pixel-point processing and pixel-group processing. Pixel-point processing presents a wide range of possibilities, including image enhancement and comparison. It is possible to alter the contrast of an image by multiplying each pixel by a constant value. This increases the contrast of an image uniformly and results in the brightening of a dark image. Conversely, pixel values can be divided by a constant to darken an overly bright or washed out image. An offset operation allows the image to be altered uniformly by adding or subtracting a constant value from each pixel. Such processing techniques could be used in a machine-vision-based door observation system to adjust images for the time of day, glare, and other environmentally induced conditions.

Dual-image pixel-point operations are used to combine two images for comparison purposes. These operations include addition and subtraction. Addition results in superimposed images while subtraction yields the differences between the captured image and the metric. The subtraction technique is the most applicable to door observation. Subtracting an image of a clear platform or car door area from a captured image would reveal obstructions or passengers blocking the doors. Providing such an image to the train operator would reduce the requirement for this person to interpret the image, because all the individual would see are the differences from the metric. Alternatively, this image could be used by an autonomous door observation system to automatically make a decision regarding the doors and implement remedial action (e.g., door cycling and automatic warning announcements).

Pixel-group processing operates on sets of pixels, normally determined by a target pixel and those adjacent. Trend information gained from these analyses can be used to emphasize detail and in morphological operations to identify shapes and object locations through edge definition techniques. The basic operation in pixel-group processing is spatial convolution, which calculates a weighted average of intensity around and including each target pixel. The range over which the average is taken is referred to as the convolution kernel and may consist of a rectangular region. The average intensity is arrived at by summing the intensity values of each pixel and dividing by the quantity included in the kernel. As with the pixel-point operations described above, the spatial convolution may include intensity adjustments through multiplicative operations to compensate for environmental factors. As a result, spatial convolutions can be computationally intensive and time-consuming; however, the spatial convolution technique could be very effective for door observation. Applying this technique to door observation, a passenger blocking the door of a rail car would significantly alter the weighted average pixel intensity of an image of the door area.

## Conceptual Sensor-Based Observation Aids

The commercial availability of a wide variety of sensors suggests that the potential for sensor-based observation aids exists. These sensors are employed in various applications ranging from industrial process control to physical security. In several of these cases, the sensors are used to detect the presence of persons or objects in a way very similar to that required for rail car side-door observation. One such example is the use of sensors for automatic opening of doors in retail establishments and other public places. The researchers explored sensing technology to identify suitable candidates and have identified the required functionality and target system architecture for this new class of observation aid. A benefit of this type of aid is that it could provide fully automated assessments of the status of the rail car side doors. Because these decisions would be based on rules embedded in hardware or software algorithms, they would help to remove much of the subjectivity associated with existing devices that include persons in the decision-making loop.

Such aids would be integrated with the door controls. Thus, the observation aid or door control system could make its own decisions on a localized, door-by-door basis and implement the required actions without train operator intervention. This would avoid the situation where the doors in the entire train need to be cycled. (Such a situation can allow additional passengers to enter the train, which causes further delays.) These systems could be used in conjunction with an advanced vehicle communication system to notify the train operator of the exact location of a problem. In addition, integration with the communication system would allow localized messages to be broadcast directly to the car or even the area of a particular car where a problem exists.

Another significant consideration with these automated systems is timing. The period when the outputs of the sensors are interrogated must be carefully established to avoid false alarms. For example, interrogation of the sensors when the train is moving would produce many false alarms. This was seen during the demonstration at Baltimore's MTA. During this demonstration, a microwave motion sensor was used and, in addition to persons, it detected the motion of the doors closing. This timing relationship is a function of many factors, including operating procedures and vehicle characteristics, such as door opening and closing speed and the extent of door pushback. At a minimum, these sensors should be interrogated when the decision is made to close the doors and before the door actuators initiate door movement. Depending on the type of sensor used, the interrogation may continue while the doors are in motion and for a time after the doors have closed. This can be accomplished by using multiple sensors (including different types) or arrays of sensors of a single type. The following paragraphs provide details on the operational scenario for sensor-based systems and discuss potential sensor technologies for use in automated door observation aids.

### *Sensor Operational Scenario*

An evaluation of the operational scenario for the sensor must begin with a characterization of the physical properties and dynamics of the objects to be sensed. The basic rule in these considerations is that the sensor cannot require contact with persons or their belongings for reliable operation. For the task of door observation, the properties of persons and objects that can be sensed are presence and motion. For the door observation application, this is interpreted as "the presence of persons or objects within the sweep of the rail car doors or persons moving toward the doors." The primary objects to be sensed include persons and their personal effects. To ensure that the system will work under all circumstances, the sensor must operate regardless of the person's physical characteristics, including clothing.

The researchers observed that behavioral characteristics of transit passengers vary significantly from property to property. Generally, in newer systems, passengers appear more safety conscious and do not stand close to the edge of the platform. In most cases, these passengers stand well clear of the warning stripes. In older systems, passenger behavior suggests familiarity almost to the point of contempt. Some passengers in these systems stand close to the platform edge and do not hesitate to lean over the edge to look for approaching trains. Selection of a sensor-based observation aid must consider the general behavior of the transit system's passengers.

With these factors in mind, the minimum presence and motion sensing zones can be established. Figure 14 shows this zone for a generic heavy rail car with three sets of doors. This zone is defined as the minimum area that must be verified as being clear before initiating train movement. In reality, this zone must be considered as being three-dimensional because a passenger could have a limb or object stuck in the doors above floor level. Figure 15 is a side view at a single door showing the elevation of the minimum observation zone.

This zone can be broader at the bottom because this is the most likely region where an obstruction would be located. It should also be noted that the sensing zone varies during the door closing process. As the doors start to close, it is desirable to detect approaching passengers while allowing those between the doors to clear. Once the doors are closed, it is desirable to detect objects stuck in the pushback range of the doors. This pushback zone is very important because, at this point, the door control system will generate a door-locked signal but small objects can still be stuck between the doors. At this time, the sensing zone becomes more of a flat plane along the side of the rail car. Persons and objects breaking this plane must be detected. This change in sensing zone requirements suggests the need for multiple sensors operating in a programmed sequence.

### *Sensor Characteristics and Technologies*

Having established the operational scenario for the sensor-based observation aid, it was possible to evaluate potential technologies. This evaluation was very broad and considered nearly 30 types of sensors. In several cases, the depth of the evaluation required in the assessment was shallow. For example, inductive sensors were immediately determined to be unsuitable because they operate by inducing and measuring eddy currents in the object to be sensed. Implicit in this operational scenario is that the object to be sensed is conductive or metal. Although this may be suitable for objects, such sensors will not sense persons. In other cases, sensor types were eliminated because their sensing ranges were below the requirements presented in Figures 14 and 15.

On the basis of this initial analysis, the researchers identified three sensor types that are suitable candidates for the application. These types are as follows:

- Microwave motion and presence sensors,
- Ultrasonic presence sensors, and
- Photoelectric presence sensors.

All devices were found to be theoretically capable of sensing persons and their personal effects on a repeatable and reliable basis. All of these sensors were tested in the laboratory to assess their performance relative to door observation aid application.

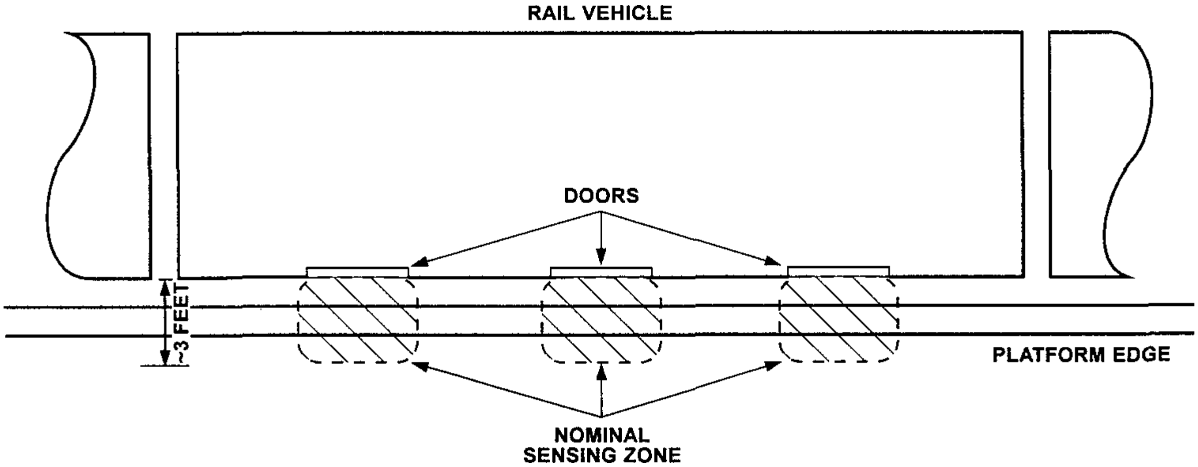


*Figure 14. Nominal sensing zone for car side-door observation (plane view).*

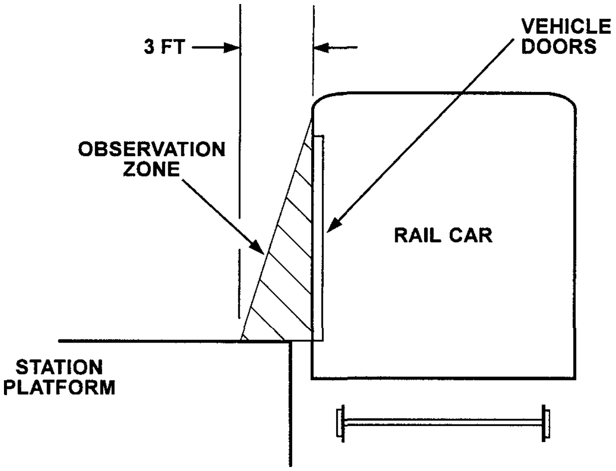


*Figure 15. Nominal sensing zone for car side-door observation (side view).*

Generally, these tests were performed by simulating rail vehicle structures and passenger movement patterns. On the basis of these tests, the microwave sensors were found to be the most suitable for use in performing tests at a transit property. This determination was based on the performance of the sensor type relative to the application, as well as the ease with which a demonstration system could be assembled and temporarily installed on a rail vehicle.

On the basis of the assessment of sensor characteristics, the microwave motion sensor was chosen for the demonstration. This sensor was found to have performance characteristics that made it best suited to the general requirements of the door surveillance application. In addition, a self-contained, battery-powered demonstration system using the microwave sensor could be easily assembled and temporarily installed in a rail vehicle without modifications to the vehicle.

In addition to the three types of sensors mentioned above, laser-based proximity sensors were identified as potentially suitable for the door observation application. Employing technology like the moving beam scanners used in retail stores, these devices could be used to measure reflected laser energy off passengers and other obstructions. As of the writing of this report, this new technology had yet to be incorporated in commercial products. It was not possible to obtain a device to perform laboratory testing, so it was not possible to address this type of device in this report. On initial evaluation, however, this technology appears promising and, as it matures, it should be considered further.

The following paragraphs describe the characteristics of microwave, ultrasonic, and photoelectric sensors and address critical parameters associated with the application. In addition, an assessment of the suitability of the sensor for the particular application is provided and potential system architectures are described.

*Microwave Sensors.* Microwave technology has proven to be a highly reliable methodology for non-contact presence sensing and motion detection of people and objects. This is performed through the detection of reflected microwave energy reaching a receiver. For proximity sensors, only the presence or absence of reflected microwave energy is detected. For motion sensors, shifts in the frequency of the microwave energy are detected according to the Doppler Principle. The researchers' analyses, laboratory testing, and experiences during the sensor demonstration on Baltimore's MTA indicate that microwave sensors have significant potential for use in the door observation application.

Industrial and commercial microwave sensors operate at frequencies around 10.525 GHz (i.e., X-band), 24.125 GHz (i.e., K-band), and 34 GHz (i.e., Ka-Band) according to FCC frequency spectrum allocations. These sensors have found widespread commercial use in applications such as intrusion alarms and automatic door openers where they are used to detect the presence of persons or objects. The microwave transmissions are immune to effects induced by environmental factors (such as humidity and temperature) and precipitation and airborne particulate matter (such as dust, rain, and snow). The research team's preliminary analyses indicate that the presence sensors hold considerable promise for automatically determining if a rail car's side doors are clear. In addition, microwave motion detectors hold promise for detecting passengers running to enter a rail car as the doors are closing.

Object detection by microwaves depends on factors such as object shape and contour and alignment of the object relative to the transmitter. Detection probability is a factor of distance; however, because the range for the door observation application is small, sufficient amounts of energy will be reflected to the receiver to ensure detection. A rule for defining what is a usable target for microwave sensors is that the circumference of the object is at least as large as the transmitted frequency wavelength. For example, X-band sensors will not detect objects with a circumference less than 1 in.

Another factor influencing detection is the target material. Materials have various dielectric, conductive, and magnetic characteristics. During laboratory testing of sensors, it was determined that the microwave sensors could sense persons and most common objects as would be seen in the mass transit environment.

Proximity sensors measure reflected microwave energy within a specific detection field by using isolated transmit and receive antennas. Most commercial devices place these two antennas in the same enclosure. Although this does not provide perfect isolation, these devices use a detection threshold to account for the energy bleed from the transmit antenna to the receive antenna. Only when the returns from the target exceed this threshold is the presence of a target indicated. In addition, the sensors employ coded transmissions to allow rejection of spurious transmissions. In this way, only energy produced by the transmitter is considered when analyzing received energy. As several point-to-point communications links and devices, such as police radar, occupy the same portions of the frequency spectra, this scheme enhances the ability of the sensor to reject spurious signals.

Motion sensors consist of transceivers that analyze the relationship between the transmitted and returned RF energy. Where motion is detected, the returned signal will exhibit a Doppler frequency shift, which is the difference between the transmitted and returned frequency. The larger the shift, the greater the velocity of the motion detected. These sensors can detect motion toward and away from them. Because there is some potential for false alarms with motion detection, most of these devices require a minimum travel distance before a motion detection signal is generated. Effectively, this averages some number of Doppler cycles before producing a motion detection output. For sensors evaluated in the laboratory, the minimum motion was approximately 3 in., which is sufficient for the door observation application.

Figure 16 provides the characteristic curve of the sensing zone for a common microwave presence sensor. This figure actually shows a narrow and a wide beam pattern. Because this figure provides a planar view, it does not illustrate that the pattern is actually three-dimensional with an elliptical cross section. When viewed from the side (i.e., projecting from the plane of the rail car side), this pattern is 12° wide. The shape of the pattern is determined by the geometry of the antenna and can be varied. In this way, a custom pattern can be developed for the door observation application to provide broader or narrower coverage should the rail car or facilities design warrant. The pattern for the motion detection sensor is similar; however, the pattern narrows more with distance—making it cigar shaped.

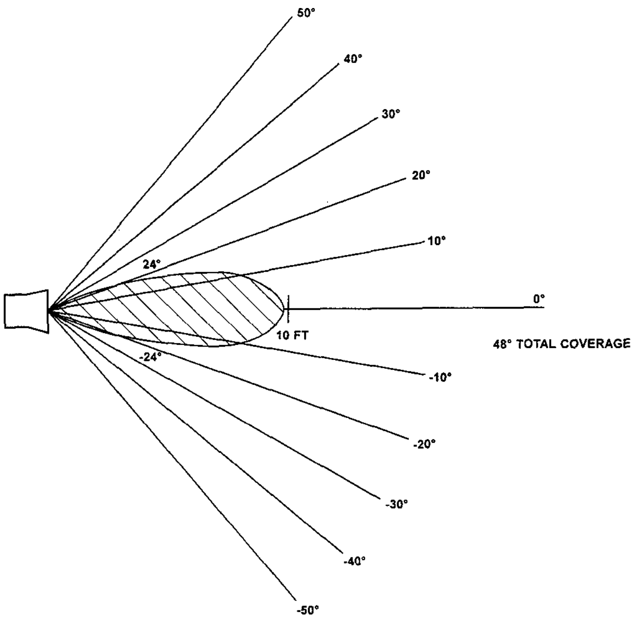


*Figure 16. Microwave sensor characteristic curve.*

Figure 17 shows this pattern overlaid against an example of a pair of rail car doors. In this example, the wide beam pattern is employed and the sensor is mounted approximately 6 in. above the door opening. Actual mounting locations will be a function of the design and structure of the rail vehicle, the right-of-way clearances, and maintenance equipment, such as car washes. As was determined during the sensor demonstration on Baltimore's MTA, the sensor can also be mounted on the inside of the rail car. Regardless of the location, it should allow the sensor radiation pattern to grow from the vehicle. As this illustration indicates, this type of sensor can provide fairly complete coverage of the door opening.

In recent years, a great deal of consideration has been given to the hazards associated with microwave radiation. All of the sensors reviewed by the researchers have emissions below the levels specified in Occupational Safety and Health Administration (OSHA) requirement 1910.97. This requirement specifies a maximum emission level of 10 mW/cm2 for microwave radiation. On average, the sensors reviewed have radiated power levels less than 5 mW/cm2.

As indicated previously, a microwave-sensor-based observation aid was tested on a light rail vehicle of Baltimore's MTA. For this test, a microwave motion sensor was mounted above the door well area, oriented so the pattern would radiate from the vehicle. The operating range of the sensor was adjusted to detect persons moving toward the doors starting at a distance of 4 ft from the side of the rail car. The sensor detected passengers walking up the door well stairs until they reached the floor level of the vehicle. Figures 18 and 19 illustrate the mounting location for the sensor.

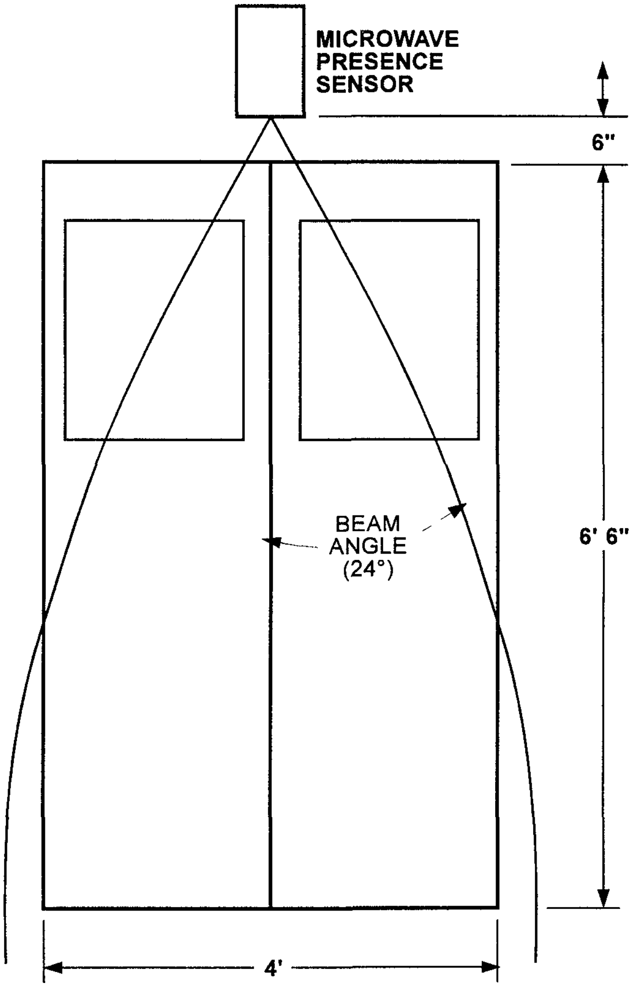


*Figure 17.* *Microwave sensor door application.*

Operational tests were conducted with the sensor in place during periods of peak (e.g., rush hour) and normal operation. During these tests, the sensor reliably detected persons moving in and out of the vehicle. In addition, the sensor did not detect persons walking by the open doors without entering. Although there was some concern going into the test regarding the reflection of microwave energy off concrete platform surfaces generating false detections, this problem did not occur.

The only situation that posed a problem was the case of the University Center/Baltimore Street Station where a railing with a metal mesh center caused reflections that resulted in erroneous detection of passengers walking by the vehicle. The railing was approximately 42 in. high and was approximately 6 ft from the side of the rail car. This railing and its proximity to the door opening are illustrated in Figure 20.

During these tests various conditions were encountered and, in each case, the sensor responded appropriately. Most notable among these circumstances was the case where a police officer jumped off the train with the doors in motion. This is analogous to a passenger running to enter the train when the

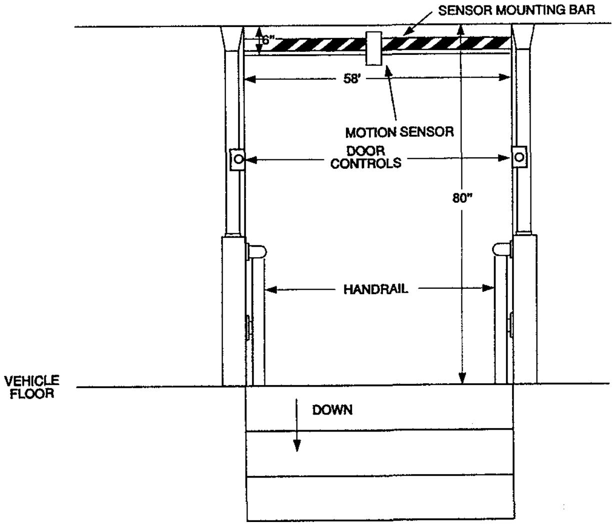


*Figure 18.* *Microwave sensor installation location—front view.*

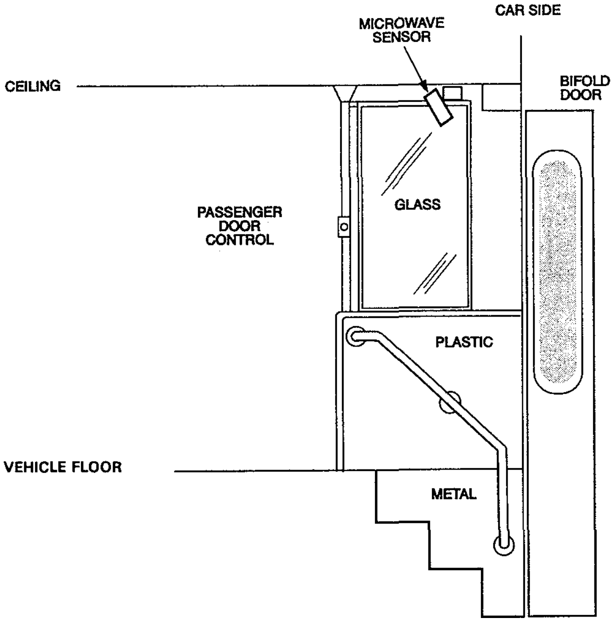


*Figure 19.* *Microwave sensor installation location—side view.*

the doors are closing. In this case, the sensor immediatel detected the police officer.

Another notable condition encountered was the case of a passenger who entered the door well and remained stationary. Although the motion sensor detected the passenger moving into the door well, it could not detect him when he was standing still. This passenger was not in danger in this location; however,

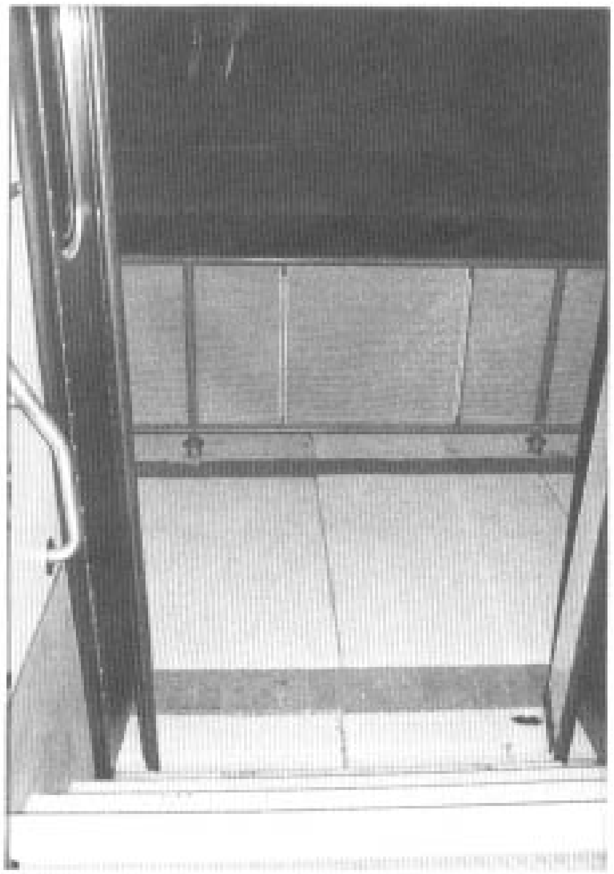


*Figure 20. University Center/Baltimore St. station railing.*

he would not have been detected if he had been between the doors and not moving.

This situation confirmed the researchers' view that multiple sensors are required to implement a fully effective sensor-based observation aid. This supports the case for using a motion sensor in conjunction with a proximity sensor to provide complete coverage of the door area. The motion sensor would detect passengers moving into the door area, while the proximity sensor would detect stationary passengers within the door sweep.

Details of the architecture and functionality of a system incorporating both types of sensors are provided later in this chapter.

*Ultrasonic Sensors.* Ultrasonic sensors are used in several noncontact proximity sensing applications. Proximity sensors can ascertain presence and distance from the sensor. As their name implies, they operate through the use of high-frequency sound waves. The sound waves are produced using a diaphragm that emits sound and detects returns of sound bouncing off persons and objects. Reflections measured above a certain threshold indicate presence of an object.

By determining the time between the sensor's emission of sound and the time the return is received and then dividing by two, the distance from the object to the sensor can be calculated using the following formula:

$$d = r \times t$$

*Where:*

$d$ = distance traveled
$r$ = rate (speed of sound)
$t$ = travel time

In general, as air becomes warmer, stationary targets appear slightly closer because increased air density causes the sound waves to move faster. Although these effects are small and probably insignificant, they can be compensated for, if necessary, through hardware or software.

The environmental characteristics of ultrasonic sensors make them well suited to transit requirements. Rain or snowfall in moderate amounts will not affect the operation of the sensor. When designing the sensor installation, however, it should be mounted so that media, such as snow or rain, are not allowed to rest on the transducer, because this will degrade the ability of the diaphragm to generate and detect sound waves.

Because the transducer determines the direction of propagation for the ultrasound waves, it will always be mounted with the transducer oriented toward the platform. Although sound is produced by compressional air waves, ultrasonic sensors are not significantly affected by wind. For example, a 30-mph wind current will deflect a sound wave from its propagation path no more than 3 percent, which is within acceptable limits for the door observation application.

As was indicated, ultrasonic sensor performance varies because of differences in the speed of sound caused by differences in ambient air temperature. This variation is generally characterized as 0.17 percent per degree Kelvin. For example, over the temperature range 20° F to 90° F, the speed of sound will vary approximately 6.6 percent. For purposes of car side-door observation, ensuring detection of the person is more important than the exact distance the person is from the sensor, which makes this variation because of temperature insignificant. As indicated previously, this can be compensated for in the system if the need arises. This could be done by using a processor to interpret the sensor data relative to variable limits. These limits could be software controlled and adjusted to compensate for factors such as temperature.

Generally, ultrasonic sensors work the best in detecting targets with a relatively high density. Solids, liquids, or granular materials work the best because of their high reflectivity. In general, porous targets, such as cloth, have high sound absorption properties and are not well suited to ultrasonic detection. Humans fall into this category. Ultrasonic sensor response is defined by characteristic curves that are a function of the distance from the sensor to the object and the angle of the object relative to the propagation path of the sound waves.

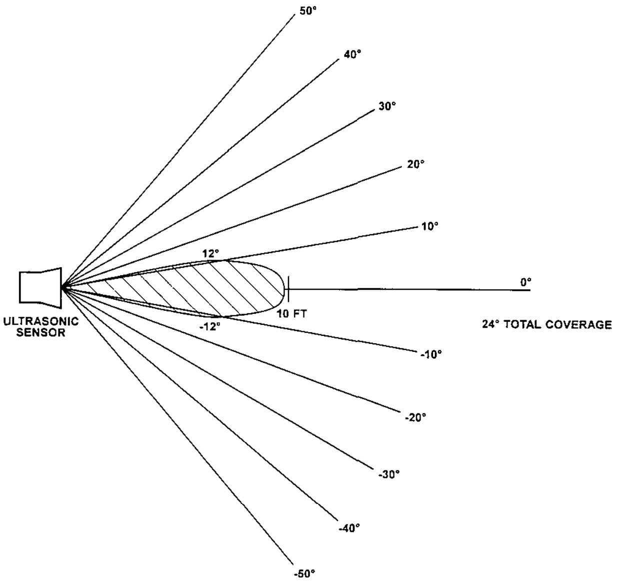


*Figure 21. Ultrasonic sensor detection characteristic curve.*

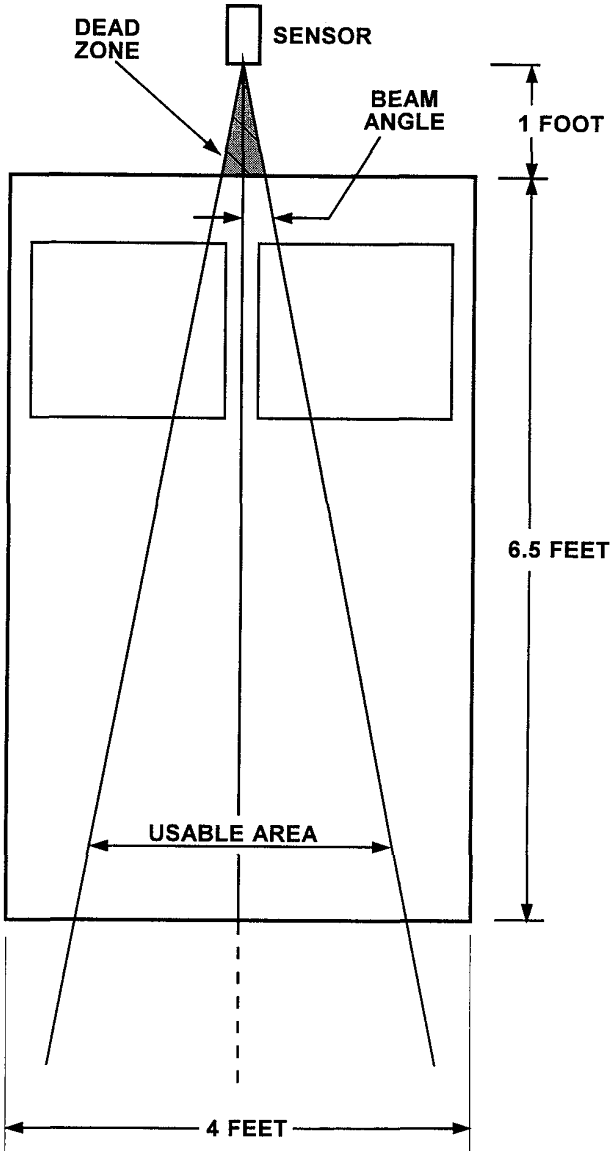


*Figure 22. Ultrasonic sensor door application.*

Figure 21 provides an example of such a characteristic curve. This curve was developed using a felt-covered tube as the target to simulate a clothed person. Although this curve defines a much lower performance envelope than that for a target such as a flat plate, it does produce acceptable performance over the short ranges associated with door observation systems.

In Figure 22, the performance envelope from Figure 21 is overlaid against an example of a subway car door. In this figure, the coverage of a commercial ultrasonic sensor is compared to the structure and geometry of an average pair of rail car doors. In this figure, the sensor is mounted approximately 1 ft above the top edge of the doors. This was done for several reasons. First, ultrasonic sensors have a dead zone close to the diaphragm where they will not provide usable information. This dead zone is a result of oscillations induced in the diaphragm when the sound wave is generated. Time must be allowed for these oscillations in the diaphragm to die before accurate readings can be made. This time defines a distance that the sound can travel before accurate readings can be obtained and this distance is the dead zone. The sensor used in the example has a dead zone of 1 ft. The second reason for mounting the sensor 1 ft above the door is to exploit the beam angle or the usable area where the sensor can detect targets. The usable area increases in cross section as the distance from the sensor increases according to the formula:

$$\text{Usable Area} = D * (\text{Cos } A)$$

*Where:*

$D$ is the distance from the sensor
$A$ is the sensor beam angle

Although ultrasonic sensors have a practical limitation on their operating range, this is not a factor in the door observation application. The standard operating pattern for ultrasonic sensors is a three-dimensional cone—not the flat plane shown in these illustrations—which will expand the observation zone from the car side into the platform area as with the microwave sensors discussed above. The shape of this zone can be varied by changing the characteristics of the transducer diaphragm.

Laboratory tests were performed with two types of ultrasonic sensors. During these tests, the sensors were tested as to their ability to reliably detect persons and objects. Testing was performed by mounting the sensor in the area above a door and observing its output as people and objects passed through its detection zone. Various sensor types, including piezoelectric and electrostatic sensors, were tested and selected methods were used to try to alter the shape of the sensors' detection patterns. These methods included placing an aperture over the sensor's diaphragm and using a horn to shape the detection pattern. Limited success was achieved with the aperture because all but the largest openings caused reflections within the sensor rendering it ineffective. Better success was achieved by using horns of various configuration to shape the detection pattern of the sensor. Discussions with sensor manufacturers revealed that most will make custom sensors with user-specified sensing ranges.

In general, the ultrasonic sensors detected the presence of stationary persons and objects and provided reasonably accurate measurements of the distance from the sensor to the object. With the objects in motion, such as persons walking at normal speed, the sensor did not reliably detect their presence. In several instances, the sensor produced false readings and, in a few instances, missed moving targets at the edges of the sensor's detection zone. This finding has significant impact on the viability of ultrasonic sensors for the door observation aid application and, as a result, the researchers do not recommend their use.

*Photoelectric Sensors.* There are several approaches to providing proximity warning using infrared and visible beams of light. In selected instances, this approach has been employed on rail vehicles. An example of this is a light rail system that uses a single set of photoeyes on their light rail vehicles to check if the door openings are clear before closing the doors. A problem the researchers see with this particular application is that the person or object must break this single beam to be detected. This leaves a considerable area where the door could be blocked but the blocking object would remain undetected. A potential solution to this problem is to employ multiple photoeyes in a crossing or some other geometric pattern to provide more complete coverage.

Such an approach is employed in the elevator industry to ensure that the doors are clear before closing. This approach employs a series of infrared beams that look across the door opening as the doors are closing. If any beam is blocked, the doors will open. Figures 23 and 24 illustrate two possible arrangements for the system. Infrared transmitters generate beams that are scanned by receivers on the opposite side. In the parallel beam configuration, the beams are separated vertically by 1.8 in.; this will provide detection of all but the smallest objects. In the crossing configuration, the separation distance is cut even further, which allows detection of even smaller objects.

While in San Francisco for the BART site visit, the researchers observed these sensor arrays in use on a hotel elevator. Following this trip, the manufacturer of the equipment was identified and a meeting was held for product discussions and a demonstration. It is always a concern with optical devices that the collection of dirt and dust will block the transmitter or receiver. During the demonstration, optical filters of various density were placed over the transmitter and receiver to block portions of the light thereby simulating the accumulation of dust or dirt.

Except for the densest filters, the infrared transmission penetrated and allowed the device to operate normally. Because there are up to 40 transmitter/receiver pairs, there also is concern that the failure of a single element will cause the device to view the doors as always being blocked. The device demonstrated could time out after a variable time. The time could be varied between 10 and 70 sec and 1 to 7 min. In this way, the device could provide some self-diagnosis of faults and implement remedial action. In addition, this feature would allow the doors to still cycle if they are intentionally held. The observation aid system would need to inform the train crew of this condition so they could choose the appropriate action to take.

Another concern with optical devices is the alignment of the transmitter and receiver. If they are out of alignment, the beams could appear broken and the doors would appear blocked.

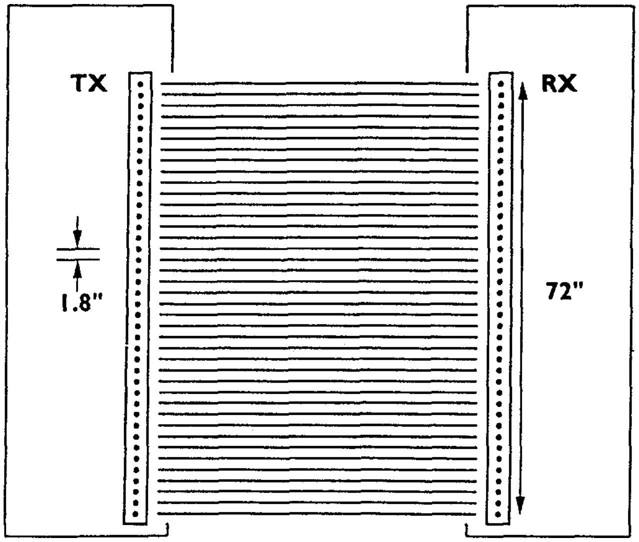


*Figure 23. Infrared array straight beam patterns.*

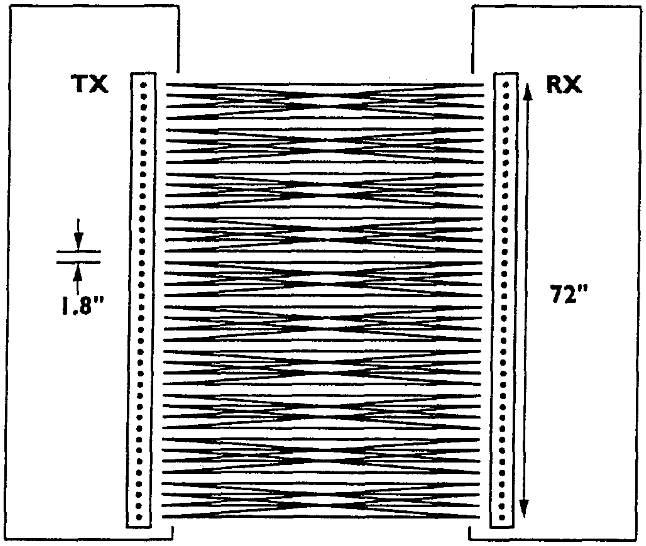


*Figure 24. Infrared array crossing beam patterns.*

Alignment becomes more critical when the transmitter and receiver elements come into contact as they would when placed on door edges. In this case, the transmitted beam cannot disperse widely and alignment becomes more critical. The devices demonstrated to the researchers have an alignment requirement of ±0.5 in. where the transmitter and receiver come into contact and ±2 in. where contact is not required. Neither of these specifications poses a problem relative to installation in a mass transit vehicle.

These devices are manufactured for use on elevator doors, which have straight edges as do most rail car doors. For car doors that are curved, it is possible to bend the transmitter and receiver array to conform to the shape of the doors. If this is done, some of the transmitters and receivers near the smallest radius of the bend may need to be relocated to ensure proper alignment.

Following the demonstration, potential application scenarios were developed for these devices. On the basis of the discussions, three potential scenarios were developed. These were placing the transmitter and receiver in the door edges, placing the device in the door frame on the exterior of the vehicle, and placing the device on the inside of the door frame. These devices have a nominal width of 5/8 in. and a depth of 1 7/8 in. making them easy to integrate into the edges of a standard rail car door. These dimensions are the same for both the transmitter array and the receiver array. Because of its relatively compact design, this device can easily be incorporated into most existing door edges. Modifications would need to be made to the style or location of the weather stripping, but this should not pose a significant technical challenge. In addition, the device could be easily incorporated into the inside or outside of the door frame.

### *Conceptual Sensor-Based Observation Aid System Design*

Having defined the operational requirements and evaluated sensor technologies, it is possible to develop a target design for a sensor-based observation system. This design can incorporate a high degree of integration and exploit the capabilities of other vehicle systems, such as automatic voice announcement and public address systems as well as the door control system. The design discussed in this section is applicable to a heavy rail vehicle with sliding doors. The door system used with the target design has a 2-sec delay after the operator activates the door-close control. During this 2-sec period, a chime or automatic door closing announcement is played.

The requirements definitions developed in the preceding paragraphs indicate that two zones must be sensed by an observation aid. These are the area between the sweep of the doors and the area outside the doors. The types of properties being sensed are different in each area. For the area outside the doors, motion is being sensed; for the area between the doors, presence is being sensed. This dictates the use of two different sensor types. The technology assessments confirmed during the demonstration indicate that a microwave sensor is best suited to the motion-sensing application while an array of photoeyes can be used to meet the presence-sensing requirement. The microwave motion sensor would be in the vehicle, with its scanning zone covering an area beginning just inside the door threshold and extending outside the vehicle for approximately 4 ft. This will allow detection of passengers approaching the doors but will not falsely detect passengers walking by the train on the station platform.

The photoeye array will be in the door frame and will cover an area starting 18 in. up from the floor level to a total height of 54 in. This zone definition allows sensing of persons ranging from small children to tall adults. Figure 25 illustrates the coverage zones for both types of sensors for the system. Depending on the type of door system and the sweep of the doors, the photoeyes will be in either the inside or outside door frame. For example, a vehicle with bifold doors that fold out can have the photoeyes in the inside door frame. Vehicles with doors that fold in will have the photoeyes in the outside door frame. For sliding doors, the photoeyes will be in the outside door frame.

Figure 26 is a block diagram of the observation aid system for a single door showing the major components and signals provided by and to external systems. A single system controller could be used to monitor all doors in a rail vehicle through the addition of input and output ports for multiple sensors. While the sensing zones for the motion and presence sensors intersect and overlap, the system controller will be interrogating them at different points in time during the door closing sequence. The major purpose of the system controller will be to implement this scheme. The algorithm used for this scheme will depend heavily on the door closing sequence.

Figure 27 illustrates the sensor-based observation aid timing sequence implemented by the system controller. In this sequence, interrogation of the motion sensor starts approximately 0.25 sec after the doors start moving. This will allow passengers entering the rail car when the doors start moving to clear the door area. Also by this time, the door closing chime, door closing message, or both will have informed passengers that the doors are closing. Interrogating the motion sensor at this time will allow detection of passengers moving toward the doors while the doors are moving.

Passengers trying to enter rail cars once the doors start moving are the most likely to be struck by or to get caught in the doors. If a passenger is detected, the doors can be recycled automatically to allow the passenger to clear or the train crew can be notified so that they can take appropriate action. Approximately 0.75 sec after the doors go in motion, the proximity sensor will be interrogated. By this time, the doors will have completed approximately one half of their sweep. If a passenger has stopped in the path of the closing doors, the proximity sensors will detect the condition.

Again, the delay between the start of the door motion and the interrogation of the proximity sensor will allow passengers sufficient time to clear the door area. Interrogation of this sensor will continue until 0.5 sec after the door lock signal is received from the door control system.

The lock signal indicates that all vehicle doors are closed. The 0.5-sec time is designed to ensure detection of a passenger attempting to pry the doors open from the outside or a passenger

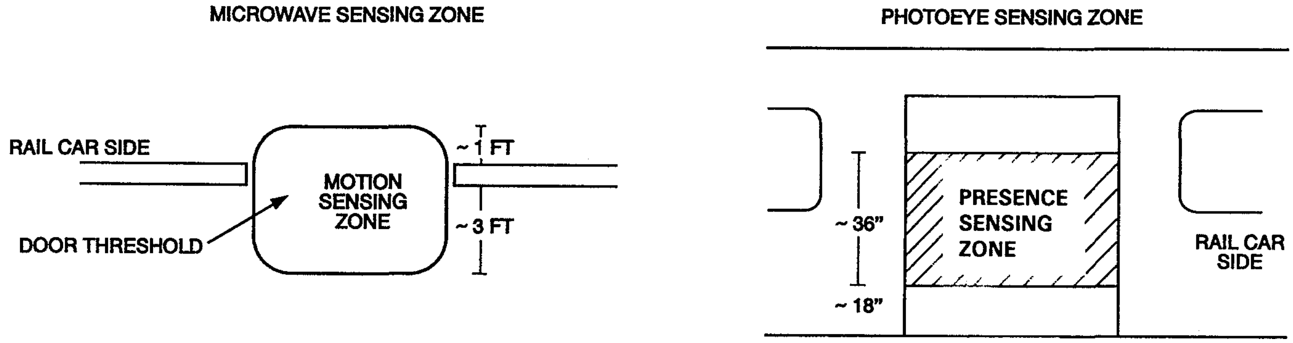


*Figure 25. Sensor coverage zones.*

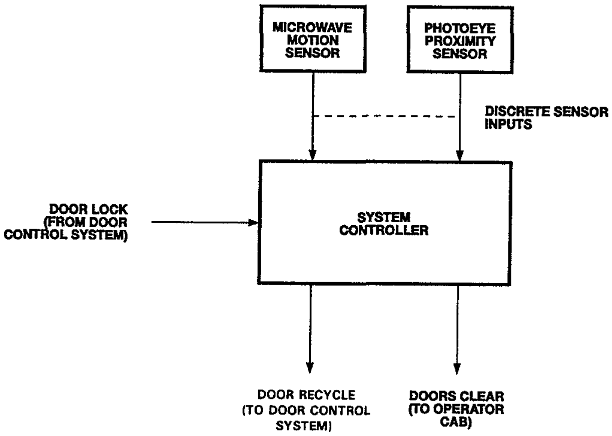


*Figure 26. Dual-sensor observation aid block diagram.*

stuck within the pushback range of the doors. After interrogation of the proximity sensor is halted, a doors clear signal will be sent to the cab to inform the train operator that it is safe to put the train in motion.

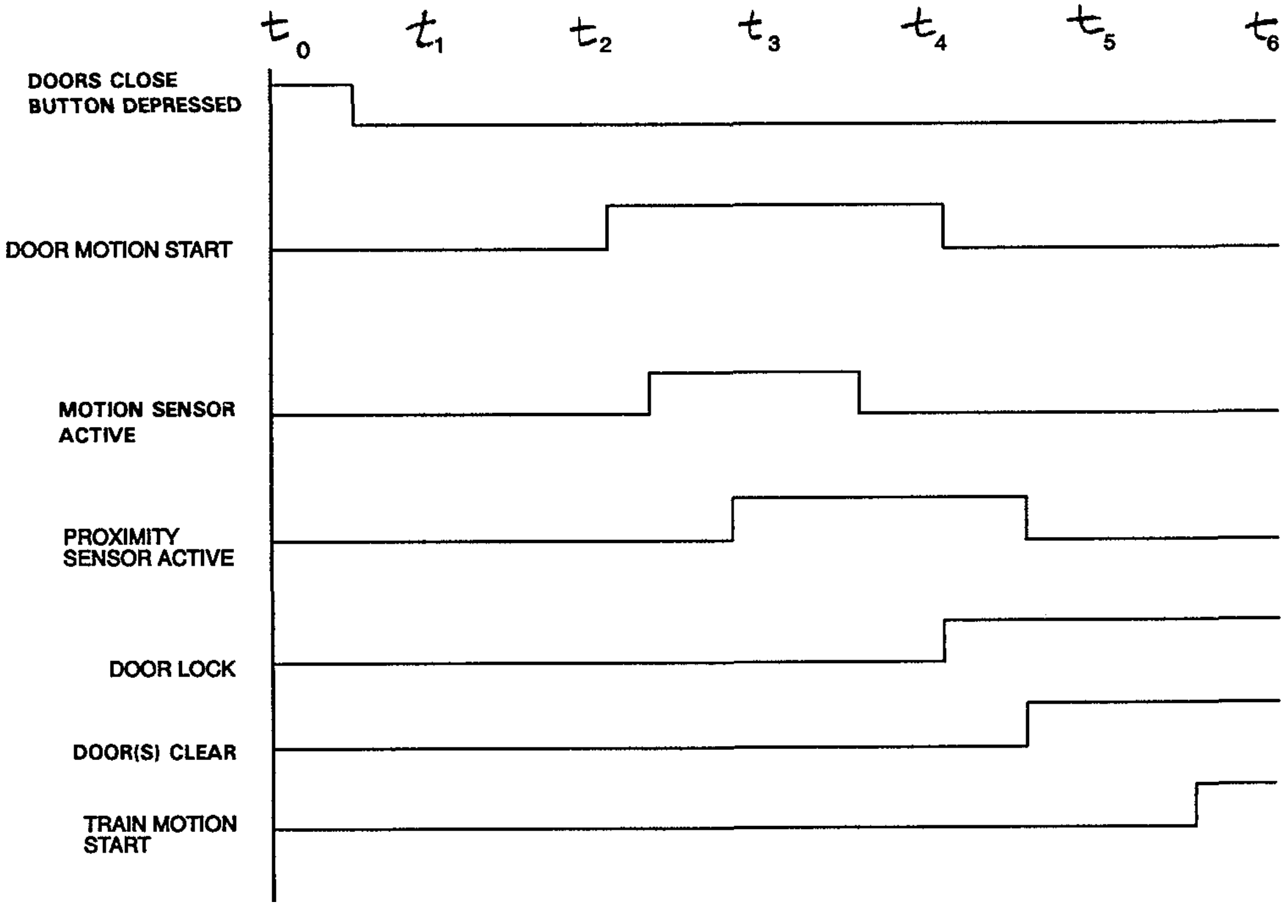


*Figure 27. Dual-sensor observation aid controller timing diagram.*