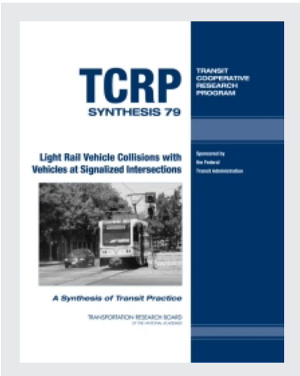


# Light Rail Vehicle Collisions with Vehicles at Signalized Intersections

## DETAILS

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## AUTHORS

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TRANSIT COOPERATIVE RESEARCH PROGRAM

# TCRP SYNTHESIS 79

# Light Rail Vehicle Collisions with Vehicles at Signalized Intersections

*A Synthesis of Transit Practice*

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SUBJECT AREAS
Public Transit

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

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2009
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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 Federal Transit Administration (FTA). A report by the American Public Transportation 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.

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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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## FOREWORD

Transit administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to the transit industry. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire transit community, the Transit Cooperative Research Program Oversight and Project Selection (TOPS) Committee authorized the Transportation Research Board to undertake a continuing study. This study, TCRP Project J-7, "Synthesis of Information Related to Transit Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute a TCRP report series, *Synthesis of Transit Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

## PREFACE

*By Donna Vlasak*
*Senior Program Officer*
*Transportation*
*Research Board*

The objective of this synthesis is to report on the mitigation methods tested and used by transit agencies to reduce collisions between light rail vehicles (LRVs) and motor vehicles where light rail transit (LRT) runs through or adjacent to highway intersections controlled by conventional traffic signals. A particular focus is placed on collisions occurring between LRVs and vehicles making left-hand turns at these intersections. The synthesis offers success stories and specific actions taken to achieve positive results, as well as examples of unsuccessful actions. The issues addressed include a range of LRT operations and environments such as median-running, side-running, contra-flow, and mixed-use LRT alignments; urban and suburban setting; and a variety of U.S. geographic regions.

This report was accomplished through a review of the relevant literature and surveys of LRT systems that took the form of structured telephone interviews. This was done, as directed by the expert topic panel, to obtain more detailed and comprehensive information about particular items and to allow the consultants to probe deeper for more complete responses. With the population for the synthesis survey being only 15 LRT systems, the consultants and expert topic panel members agreed that this would be the best approach.

Kelley Klaver Pecheux, Science Applications International Corporation, McLean, Virginia, and Harry Saporta, PB Americas, Inc., Washington, D.C., collected and synthesized the information and wrote the paper, under the guidance of a panel of experts in the subject area. The members of the Topic Panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

## CONTENTS

# LIGHT RAIL VEHICLE COLLISIONS WITH VEHICLES AT SIGNALIZED INTERSECTIONS


## SUMMARY

At their start-up, new light rail transit (LRT) operating systems typically experience undesirable frequencies of light rail vehicle (LRV)–motor vehicle collisions, particularly where motor vehicles cross LRT tracks located in or adjacent to highway intersections that are controlled by conventional traffic signals (i.e., street-running operations). Over time, as agencies have gained experience with LRT operations, they have addressed the problems through engineering, education, and enforcement efforts. This report is a synthesis of today's state of the practice with regard to mitigating collisions between LRVs and motor vehicles at signalized intersections. This synthesis will help transit agencies to better understand, and to learn from, the experiences of other agencies facing similar challenges.

The objective of this study was to report on the mitigation methods tested and used by transit agencies to reduce collisions between LRVs and motor vehicles where LRT runs through or adjacent to highway intersections controlled by conventional traffic signals, with a particular focus on collisions occurring between LRVs and vehicles making left turns at intersections. This synthesis includes success stories and specific actions taken to achieve positive results, as well as examples of unsuccessful actions. The issues addressed include a range of LRT operations and environments (median-running, side-running, contra-flow, and mixed-use LRT alignments), urban and suburban settings, and a variety of U.S. geographic regions.

As directed by the topic panel, the technical approach for this synthesis project included a review of recent relevant literature as well as structured telephone interviews with the following transit agencies:

- Tri-County Metropolitan Transportation District of Oregon (TriMet)—Portland, Oregon;
- Denver Regional Transportation District (RTD);
- Metropolitan Transit Authority of Harris County (METRO)—Houston, Texas;
- Los Angeles County Metropolitan Transportation Authority (LACMTA);
- New Jersey Transit—Hudson–Bergen Light Rail;
- Sacramento Regional Transit District (RT); and
- Dallas Area Rapid Transit (DART).

A review of the most recent literature and structured interviews with these transit agencies revealed that collision types and circumstances vary between agencies, depending on a variety of factors. However, transit agencies with LRT systems consistently reported that most collisions between LRVs and motor vehicles are caused by motorists making illegal or improper turns or running red lights. The most common scenarios of left-turn and right-angle collisions at signalized intersections have been categorized as the following:

- Motorists in left-turn pocket lanes violate the red left-turn signal indication and collide with LRVs approaching from behind.
- Motorists make illegal left turns against static no left-turn signs (at locations where turns are prohibited) and collide with LRVs approaching from behind.
- Motorists violate active turn-prohibition signs and train-approaching warning signs in conflict with LRV operation (at locations where turns are permitted or prohibited).

- Motorists make left turns from adjacent through-only lanes instead of from the lanes shared with the LRVs (mixed-use alignment).
- Drivers encroach on or stop on the tracks and are struck by an LRV (coming from either direction) at a right angle (side-running alignment only).
- Drivers run a red signal indication and collide with an LRV (coming from either direction) at a right angle.

Transit agencies have taken a number of approaches and have implemented a variety of countermeasures to mitigate collisions between LRVs and motor vehicles at signalized intersections. These countermeasures include physical barriers, traffic signs, signal displays, traffic signal phasing, pavement markings and/or treatments, public outreach and/or education, police and photo enforcement, and others such as lower train speeds, standardized crossings, and LRV operator defensive driving. This synthesis report describes 34 countermeasures and presents case studies of recent applications of many of the countermeasures by transit agencies. Although some of these countermeasures have been more effective than others, there have been few empirical studies conducted to examine the effectiveness of the countermeasures in terms of reducing the frequency and severity of collisions.

Despite the efforts put forth by transit agencies and city and county traffic engineering departments, collisions between LRVs and motor vehicles at signalized intersections continue to occur, and agencies continue to seek out innovative countermeasures in an effort to further reduce the frequency and severity of these collisions.

CHAPTER ONE

# INTRODUCTION

At start-up, new light rail transit (LRT) operating systems typically experience undesirable frequencies of light rail vehicle (LRV)–motor vehicle collisions, particularly where motor vehicles cross LRT tracks located in or adjacent to highway intersections that are controlled by conventional traffic signals. Over time, as agencies have gained experience with LRT operations, they have addressed the problems by making changes to pavement markings, signs, signals, street geometrics, operating procedures, and training programs. This report is a synthesis of today's state of the practice with regard to mitigating collisions between LRVs and motor vehicles at signalized intersections. This synthesis will help transit agencies to better understand and to learn from the experiences of other agencies facing similar challenges.

## OBJECTIVE

The objective of this study was to report on the mitigation methods tested and used by transit agencies to reduce collisions between LRVs and motor vehicles where LRT runs through or adjacent to highway intersections controlled by conventional traffic signals, with a particular focus on collisions occurring between LRVs and vehicles making left turns at these intersections. This synthesis includes success stories and specific actions taken to achieve positive results, as well as examples of unsuccessful actions. The issues addressed include a range of LRT operations and environments (median-running, side-running, contra-flow, and mixed-use LRT alignments), urban and suburban settings, and a variety of U.S. geographic regions.

## TECHNICAL APPROACH

The technical approach for this synthesis project included a review of recent relevant literature, as well as a survey of selected light rail systems. Regarding the relevant literature, two documents form the basis for improving light rail safety within city streets and in semi-exclusive rights-of-way: *TCRP Report 17: Integration of Light Rail Transit into City Streets* (*1*) and *TCRP Report 69: Light Rail Service: Pedestrian and Vehicular Safety* (*2*). *TCRP Report 17,* published in 1996, was a comprehensive study of 10 LRT systems across North America, and included a literature review, structured interviews of the transit agencies, accident analyses, and recommendations for improving safety of LRT operations within city streets. It addresses the safety and operating experience of LRT systems operating on shared rights-of-way at speeds generally less than 35 mph. *TCRP Report 69,* published in 2001, documents and presents the results of a comprehensive study to improve the safety of LRT in semi-exclusive rights-of-way where LRVs operate at speeds greater than 35 mph. The analysis presented in this report is based on interviews with LRT agency officials, field observations, and analysis of accident records and accident rates at 11 LRT systems in the United States and Canada. The report presents guidelines that may be considered in planning and designing new LRT systems or in retrofitting and extending existing LRT systems.

The research for *TCRP Report 17* and *TCRP Report 69* was conducted more than 7 and 12 years ago, respectively. Since that time, many of the systems interviewed for these studies have expanded, and other new systems have begun service or are about to begin service. Thus, the research conducted for this synthesis report identified the current state of the practice by focusing primarily on studies that have been conducted since these earlier studies, while using the results from these earlier studies as a baseline.

Two additional and particularly relevant sources referenced throughout this synthesis include a research paper, *Median Light Rail Crossings: Accident Causation and Countermeasures* (*3*) and the *METRORail Traffic Safety Assessment* (*4*), both of which offer insight into the issues surrounding LRV–motor vehicle collisions at signalized intersections, as well as a variety of countermeasures for mitigating these types of collisions.

To supplement the recent relevant literature, a survey of LRT systems was undertaken. The surveys were administered by means of the telephone in the form of structured interviews. Structured telephone interviews were chosen over a written survey for a number of reasons. First, considering the topic, it was important to obtain detailed information about particular problematic intersections, collision circumstances, measures taken to mitigate the collisions, and effectiveness of the countermeasures. Structured telephone interviews allowed the researchers to probe those being surveyed for more complete responses, resulting in more detailed and comprehensive information. Second, although there are more than 30 agencies that operate rail systems in semi-exclusive or mixed traffic environments, only approximately 20 are LRT systems (as opposed to trolley or street car systems), and of these systems, only about 15 were appropriate to include in this study (one system had no operating history, with an opening day of

November 2007; several others operated primarily in exclusive rights-of-way; and some had only gated crossings at signalized intersections). With the population for the survey being only about 15 systems, the researchers and panel members agreed that structured telephone interviews with a carefully selected sample of these systems would be the best approach for this synthesis.

Nine LRT systems were selected and contacted for participation in the survey. These nine agencies were selected based on three criteria: collision history/frequency, operating environment, and system age. They represented a range of collision experience, including systems with relatively low collision frequencies (i.e., those that are controlling collisions), as well as those that initially had problems, but have shown reductions in collision rates over the years. Their operating environments included a range of alignments (median-running, side-running, mixed-use, and contra-flow), geographic locations, and urban settings (central business district, suburban). Finally, the age of the systems selected ranged from one that has been operational for more than 20 years to one that has been operational for only 4 years. Of the nine systems contacted, the following seven systems participated in the telephone interviews:

- Tri-County Metropolitan Transportation District of Oregon (TriMet)—Portland, Oregon;
- Denver Regional Transportation District (RTD);
- Metropolitan Transit Authority of Harris County (METRO)—Houston, Texas;
- Los Angeles County Metropolitan Transportation Authority (LACMTA);
- New Jersey Transit—Hudson–Bergen Light Rail;
- Sacramento Regional Transit District (RT); and
- Dallas Area Rapid Transit (DART).

Some of these agencies were also interviewed for the development of *TCRP Reports 17* and *69.* Table 1 shows the overlap in the LRT systems that were included in *TCRP Report 17, TCRP Report 69,* and this synthesis project.

The primary objective of the structured interviews for this synthesis was to identify the current state of the practice at each agency for mitigating LRV–motor vehicle collisions at signalized intersections. For the older systems, the interviews served to obtain an update on what improvements had been implemented over the past decade since the previous TCRP research studies were conducted, including experiences with system expansions. For the newer systems, the interviews served to identify start-up experiences.

Before administering the telephone survey, agency representatives were contacted through e-mail to provide background to the synthesis project, to invite them to participate in the research, and to schedule an interview time. The interviews generally lasted between 30 min and 1 h. Five main topics were covered during the interviews:

- History of LRT operations (e.g., when LRT operations began, when expansions occurred).
- LRT operating environment (e.g., LRT alignments; number of signalized intersections through which the LRT operates; number of intersections with crossing gates, signal operations, existing traffic control).
- LRT–motor vehicle collision history (frequency and type of collisions, common causal factors).
- Mitigating collisions between LRVs and motor vehicles at signalized intersections (e.g., countermeasures tested or implemented, effectiveness).
- Recommendations for other agencies with start-up systems or those experiencing problems with collisions at signalized intersections.

During the interviews, the interviewees' responses to questions were recorded and detailed notes were taken. Following the interviews, each person interviewed was sent a summary of the interview that they reviewed for accuracy and completeness.

## SYNTHESIS ORGANIZATION

This synthesis report is organized into five chapters. Following this introductory chapter is chapter two that includes discussions of the most common types of collisions between LRVs and motor vehicles at signalized intersections and the contributing factors to LRV–motor vehicle collisions at signalized intersections. Chapter three then provides details regarding a large array of countermeasures tested and/or used by transit agencies to mitigate collisions between LRVs and motor vehicles at signalized intersections. Countermeasures include physical barriers, traffic signal phasing, signs, LRT and traffic signal displays, pavement markings and/or treatments, public outreach and education, and enforcement. Chapter four contains case studies that present the most recent challenges by select transit agencies regarding LRV–motor vehicle collisions at signalized intersections, including successful countermeasures where applicable. Finally, chapter five presents a summary of the conclusions drawn from the research effort.

TABLE 1
LRT SYSTEMS REVIEWED IN TCRP RESEARCH

| Agency/LRT System | Began Operation | *TCRP Report 17* (1996) | *TCRP Report 69* (2000) | *TCRP Synthesis 79* (2008) |
|---|---|---|---|---|
| Massachusetts Bay Transportation Authority (Boston) | 1889/1897 | √ | | |
| San Francisco Municipal Transportation Authority/Muni | 1897/1981 | √ | | |
| Edmonton Transit System/LRT | 1978 | | √ | |
| San Diego Trolley | 1981 | √ | √ | |
| Calgary Transit/C-Train | 1981 | √ | √ | |
| Niagara Frontier Transportation Authority (Buffalo)/Metro Rail | 1984 | √ | | |
| **Tri-County Metropolitan Transportation District of Oregon (TriMet)—Portland** | 1986 | √ | √ | √ |
| Santa Clara Valley Transportation Authority | 1987 | √ | √ | |
| **Sacramento Regional Transit District (RT)** | 1987 | √ | √ | √ |
| **Los Angeles County Metropolitan Transportation Authority (LACMTA)** | 1990 | √ | √ | √ |
| MTA (Baltimore)/Light Rail | 1992 | √ | √ | |
| Metro (St. Louis)/MetroLink | 1993 | | √ | |
| **Denver Regional Transportation District (RTD)** | 1994 | | √ | √ |
| **Dallas Area Rapid Transit (DART)** | 1996 | (Not operational at the time) | √ | √ |
| **New Jersey Transit—Hudson–Bergen Light Rail** | 2000 | (Not operational at the time) | | √ |
| **Metropolitan Transit Authority of Harris County (METRO)—Houston** | 2004 | (Not operational at the time) | (Not operational at the time) | √ |

Note: Boldface type indicates transit agencies that were interviewed for this synthesis project.

CHAPTER TWO

# COLLISIONS BETWEEN LIGHT RAIL VEHICLES AND MOTOR VEHICLES AT SIGNALIZED INTERSECTIONS

The placement of LRT in the middle of, adjacent to, or within an urban street can lead to complex crossings incorporated into signalized highway intersections. Although these intersections are typically protected with conventional traffic signals and supplemental signage regarding the LRT, they do not operate like conventional crossings, nor do they operate like conventional signalized intersections. Rather, they are intersections with unique operating characteristics that have proven to create problems that can lead to collisions between LRVs and motor vehicles, especially when turning maneuvers are involved.

## LIGHT RAIL TRANSIT ALIGNMENT THROUGH SIGNALIZED INTERSECTIONS

The diagrams in Figure 1 illustrate a few examples of how LRT can be incorporated into urban street signalized intersections. The diagrams include a median-running alignment, two side-running alignments, and a mixed-use alignment. Although each of the diagrams shows dual tracks, any of these alignments could include single-track operation and other variations in the number of traffic lanes where there are traffic movements. These diagrams are shown for example purposes only. Even though there are common challenges among the different alignments, each presents its own unique challenges, which are discussed in more detail here.

### Median-Running Alignments

In median-running alignments (Figure 1*a*), LRVs operate between the parallel, two-way lanes of an urban street. The LRT right-of-way typically is unpaved (except at designated locations where motor vehicles cross the light rail tracks) and is separated from the roadway by curbs, and in some cases, fencing. Left-turn pocket lanes for motor vehicles are typically provided in the parallel running roadways. Motor vehicle movements are controlled by traffic signals. Left-turn motor vehicle movements are protected through the use of left-turn-only traffic signal phases so as to control motor vehicle movements that conflict with LRVs. Reports of violations of the left-turn signal by motorists are not uncommon at these intersections. Collisions typically occur when motorists disregard, do not perceive, or misinterpret the left-turn signal and are unaware that an LRV in the median is approaching the intersection from behind. Although less common, collisions also occur when a motorist intending to turn left at an intersection turns in front of an LRV approaching the intersection from the opposite direction. Cross traffic red-light running is also of concern at these intersections.

### Side-Running Within Roadway Right-of-Way

Side-running LRT within the roadway right-of-way (Figure 1*b*) operates on a paved guideway within the roadway boundaries of one-way streets. The LRT guideway may be separated from the roadway by a curb or other physical features except for where motor vehicles must cross the light rail tracks to turn onto the cross street. Challenges encountered at these intersections are dependent on whether the LRT right-of-way is located to the left or right of the one-way traffic running parallel to the tracks. With LRT alignments to the left of the roadway, left turns in front of LRVs approaching on the left from behind are the most prevalent accident type, as motorists may be unaware of the presence of the LRV. Similarly, right turns in front of LRVs approaching on the right from behind are the most common incidents occurring when LRT alignments are to the right of the roadway. As with other intersections, cross-street traffic disobeying traffic signals can also be problematic. Side-running alignments have the added challenge of vehicles encroaching onto the tracks where the tracks cross the cross-street approach.

### Side-Running Adjacent to Roadway

Side-running adjacent to a roadway (Figure 1*c*) are LRT alignments located outside of a roadway right-of-way. As with side-running LRT alignments within the roadway right-of-way, the guideway may be physically separated from the roadway by a curb, landscaping, and/or fencing. Unlike side-running within the roadway right-of-way, two-way traffic flow on the adjacent roadway is common. Challenges are similar to those of side-running within the roadway right-of-way—motorists turning in front of LRVs approaching an intersection from behind the motorist, vehicles encroaching onto the tracks on the cross-street approach, and motorists running red lights on the cross-street.

### Mixed-Use Alignments

Generally in mixed-use alignments (Figure 1*d*), motor vehicles and LRVs share the same travel lanes. It is not uncom-

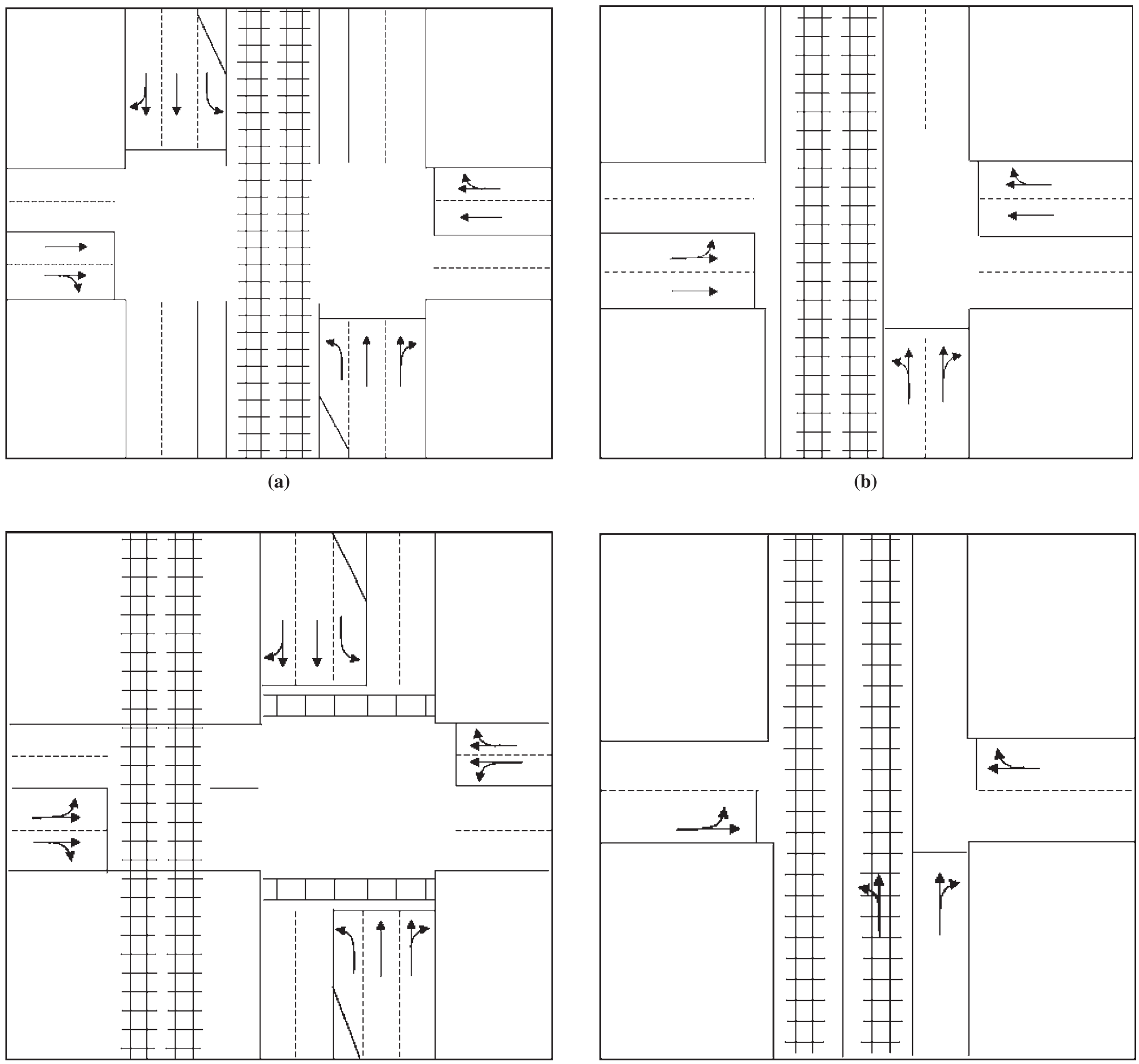


FIGURE 1 Examples of common LRT alignments through signalized intersections: median-running (*a*), side-running within roadway right-of-way (*b*), side-running adjacent to roadway (*c*), and mixed-use (*d*).

mon, however, for lanes to be designated as "LRV Only" lanes, with vehicular traffic running parallel to the LRT right-of-way. The LRV-only lane is differentiated from the roadway by signage and striping, contrasting colored pavement, mountable curb, rumble strips, traffic buttons, or other tactical treatment. Motor vehicle turning movements for parallel running traffic may be from the same lane in which the LRV is operating or from the adjacent lane to the LRT. In either case, only when it is clear and LRV operators are assured that there are no conflicting moves, are they required to proceed through the intersection with caution. Conflicting turning movements may be controlled by displaying red traffic signals for all directions of motor vehicle traffic when an LRV is passing through the intersection, by permitting the conflicting move only after the LRV has passed through the intersection, or by prohibiting turning movements across the LRT altogether. Challenges in mixed-use alignments are similar to those without LRT operations: motorist attempts to overtake and turn left in front of LRVs, motor vehicle traffic from the opposite direction turning suddenly in front of an approaching LRV, and cross traffic violating the red traffic signal.

## PROBLEMS BETWEEN LIGHT RAIL VEHICLES AND MOTOR VEHICLES AT SIGNALIZED INTERSECTIONS

The 1996 review of 10 LRT systems for *TCRP Report 17* identified the principal problems between LRVs and motor vehicles at signalized intersections. These problems covered a range of issues, including LRT alignment and complex intersection geometry; traffic signal timing and pre-emption of the left-turn phase; and driver factors such as expectancy, confusion, and risk-taking (*1*). These issues could play a role in the occurrence of LRV–motor vehicle collisions. Although these issues were identified in the research conducted more than 12 years ago, most of these issues are challenges that many transit agencies still experience today.

## ROLE OF THE MOTORIST IN LIGHT RAIL VEHICLE–MOTOR VEHICLE COLLISIONS

Transit agencies with LRT systems consistently report that most collisions between LRVs and motor vehicles are caused by motorists making illegal or improper turns or running red lights. Although there have been special considerations given to safety in the design and operation of LRT systems, motorists continue to exhibit risky behavior and ignore traffic control devices at LRT crossings.

In a working paper developed for California Partners for Advanced Transit and Highways (PATH) (*3*), the authors reported that one of four critical events on the part of the motorist must occur before a left-turn collision with an LRV at a median-running crossing. These critical events include:

- Disobedience—An inappropriately low perception of risk and expectations from conventional intersections contribute to driver disobedience. For example, motorists may violate static “No Turn on Red” signs at conventional intersections with little to no consequences; however, when the perception of risk and expectation from this situation at a conventional intersection is transferred to an intersection with LRT, the same action can have more serious consequences.
- Failure to perceive—This occurs when motorists do not observe the traffic control devices. For example, a motorist who sees the adjacent through-traffic’s signal turn green and the through vehicles proceed into the intersection may not perceive that the left-turn signal is red owing to an approaching LRV.
- Misinterpretation—Misinterpretation accidents are related to expectation errors and cognitive limitations of motorists, and they can be more likely to occur at complicated intersections such as those that incorporate LRT.
- Violation of drivers’ expectations—When driver expectancy is violated, it can lead to accidents. Drivers grow accustomed to intersections operating in a certain way, which may lead them to anticipate movements. For example, in an area where leading left turns are used predominately, a collision between an LRV and a motorist turning left could occur if the motorist proceeds into the intersection in anticipation of the leading left-turn phase only to discover that it has been pre-empted by an approaching LRV. In other words, drivers’ expectations affect driver behavior.

## TYPES OF COLLISIONS OCCURRING BETWEEN LIGHT RAIL VEHICLES AND MOTOR VEHICLES AT SIGNALIZED INTERSECTIONS

Collision types and circumstances tend to vary between agencies, depending on a variety of factors including the environment, the initial incorporation of LRT into the city streets, driver types and attitudes, and traffic control. Consequently, accident type prevalence differs among transit agencies. However, transit agencies with LRT systems consistently report that most collisions between LRVs and motor vehicles are caused by motorists making illegal or improper turns or running red lights.

### Left-Turn Collisions

Motor vehicles that make illegal turns in front of approaching LRVs account for the greatest percentage of total collisions for most LRT systems (*5*). Data from 1998 show that motorists making improper left turns in front of light rail trains caused 62 accidents, 47% of all LRV–motor vehicle accidents. This accident occurrence pattern is not specific to intersections with LRT, but is consistent with motor vehicle accident experience at intersections in general. The California Public Utilities Commission found that the second most common cause of LRV–motor vehicle accidents was the problem of motor vehicles running red lights or driving around gates (*6*).

In a traffic safety assessment that took place 1 month after Houston’s METRORail began operation, researchers stated that the most common type of collision between motor vehicles and METRORail vehicles involved illegal left-hand turns by motorists. Despite traffic signs and signals designed to control the location and timing of left-turn movements along the rail line, several motorists turned into or in front of oncoming LRVs, sometimes turning from an incorrect lane. All collisions examined appeared to have been the result of improper or illegal turns or other driver errors. Illegal left turns are a primary source of motorist–LRV collisions in other light rail systems as well (*5*).

### Right-Angle Collisions

A paper presented at the 2006 APTA Rail Conference discusses stop bar violations on the cross-street approaches to intersections with LRT crossings (*7*). It describes the special considerations given to safety in the design and operation of the LRT system; however, motorists continue to exhibit risky behavior and ignore traffic control devices at LRT–roadway crossings. Risky behavior includes the failure of motorists to acknowledge traffic signals, to obey active warning devices, and to stop within clear zones—all of which can lead to right-angle collisions between LRVs and motor vehicles.

## COMMON LIGHT RAIL VEHICLE–MOTOR VEHICLE COLLISION SCENARIOS

Considering the many different types of street-running operations of LRT, there are many different scenarios of possible collisions between LRVs and motor vehicles at signalized intersections. However, the most common types of collisions are motor vehicles making illegal or improper left turns in front of LRVs and right-angle collisions with vehicles on the cross streets; therefore, they are the focus of this synthesis.

Based on a review of the most recent literature and interviews with selected transit agencies for this research, the most common scenarios of left-turn and right-angle collisions at signalized intersections can be categorized as the following:

- Motorists in left-turn pocket lanes violate the red left-turn signal indication and collide with LRVs approaching from behind.
- Motorists make illegal left turns against static no left-turn signs (at locations where turns are prohibited) and collide with LRVs approaching from behind.
- Motorists violate active turn-prohibition signs and train-approaching warning signs in conflict with LRV operation (at locations where turns are permitted/prohibited).
- Motorists make left turns from adjacent through-only lanes instead of from the lanes shared with the LRVs (mixed-use).
- Drivers encroach on or stop on the tracks and are struck by an LRV (coming from either direction) at a right angle (side-running alignment only).
- Drivers run a red signal indication and collide with an LRV (coming from either direction) at a right angle.

Table 2 presents each of these six collision scenarios along with a list of possible causes of each scenario. The following section presents a number of countermeasures that can be implemented to mitigate the occurrence of these collision scenarios.

TABLE 2
COMMON COLLISION SCENARIOS AND POSSIBLE CAUSES

| Collision Scenario | Possible Causes |
|---|---|
| Motorists in left-turn pocket lane violate the red left-turn signal indication and collide with LRVs approaching from behind. | Signs do not convey to motorists why they are not allowed to turn. |
| | Motorists initiate their left turns against the signal as soon as the cross-street traffic receives the red (particularly common at locations with leading left-turn phases). |
| | Motorists in the left-turn lane mistake the through-traffic signals for those controlling the left-turn movement. |
| | Motorists in the left-turn lane cue off of the movement of the through vehicles. |
| | Motorists make left turns across the LRT right-of-way immediately after termination of their green left-turn arrow. |
| | Motorists confuse LRT signals with traffic signals. |
| | Where traffic signals are pre-empted during the left-turn phase, motorists may incorrectly assume that the signal failed and violate the signal. |
| Motorists make illegal left turns against static no left-turn signs and collide with LRVs approaching from behind. | There may be too few locations to make left turns across the tracks leading to increased pressure to turn left where such movements can be made, even if prohibited. |
| | Left turns were previously allowed before the LRT system was constructed. Permanently prohibiting a traffic movement that was previously allowed disrupts normal, expected travel patterns. |
| | Motorists who are used to violating regulatory signs with little consequence at conventional signalized intersections need to better understand the risks of violating turn prohibitions at intersections with LRT. |
| | There are too many signs at intersections. Multiple signs increase driver information processing time and increase the potential for missing important information. |
| | Traffic control devices place an emphasis on prohibited rather than permitted movements. Drivers may be confused about where they can make turn movements and where a through movement is the only permitted movement. |
| Motorists violate active turn-prohibition signs and train-approaching warning signs in conflict with LRV operation. | Signs may be activated too far in advance of the LRV arrival. If motorists perceive that the LRVs do not come even when the signs are active, they may lose respect for the signs and turn in conflict with an LRV. |
| | Signs may be activated too late to provide sufficient advance warning to motorists. |
| | Motorists do not understand why the signs are on and/or why turns are prohibited. Permitting movements at some times and prohibiting them at others causes driver confusion. |
| Motorists make left turns from through lanes instead of adjacent or lanes shared with the LRVs. | Drivers are confused about which lane to turn from. Failure to understand the proper behavior at these locations may lead to vehicle–train conflicts. |
| Drivers encroach on or stop on the tracks and are struck by an LRV (coming from either direction) at a right angle. | Having too many transverse markings on the roadway in the vicinity of the intersection (e.g., crosswalk, stop line, railroad markings) can cause confusion about where to stop. |
| | Motorists may not perceive the LRT tracks crossing the roadway on the approach to the intersection. |
| | Motorists attempt right or left turns on red and stop on the tracks to wait for a gap in traffic as the LRV approaches. |
| Drivers run a red signal indication and collide with an LRV (coming from either direction) at a right angle. | Motorists are unaware an LRV is coming or speed through the intersection in an attempt to beat an approaching LRV. |

CHAPTER THREE

# COUNTERMEASURES TO MITIGATE COLLISIONS BETWEEN LIGHT RAIL VEHICLES AND MOTOR VEHICLES AT SIGNALIZED INTERSECTIONS

This chapter focuses on the countermeasures used to mitigate collisions between LRVs and motor vehicles at signalized intersections. According to Coifman and Bertini (*3*), a countermeasure for mitigating collisions between LRVs and motor vehicles should address motorists' expectations at conventional intersections as well as work to keep motorists within the law at LRT crossings. They go on to state,

> A successful collision countermeasure should accomplish at least one of the following goals:
>
> Remind the driver that there are special risks in the given situation
> Physically prevent the driver from taking these additional risks (*3,* p. 4).

Table 3 shows a variety of countermeasures, found in a review of the literature and through interviews with selected transit agencies, which have been tested, implemented, or suggested to mitigate collisions between LRVs and motor vehicles at signalized intersections. The sections that follow provide details on each of these countermeasures.

## PHYSICAL BARRIERS

Physical barriers provide physical separation between movements. Transit agencies have employed a variety of physical barriers, including gates, bollards, and delineators to provide physical separation between LRV and motor vehicle movements. These countermeasures are discussed here.

### Gates

An FTA-sponsored study was undertaken in 2002 to investigate the use of railroad crossing gates to reduce collisions between LRVs and motor vehicles at intersections where streets run parallel to LRT and motorists are permitted to make left turns across the tracks (*8*). The two types of gates included in the study were:

- Left-turn gates, which can be used to physically prohibit motorists from turning left in conflict with an LRV. Left-turn gates can be installed parallel to the tracks (along the line separating the left-turn lane from the tracks in a median-running environment) or at 90 degrees to the left-turn lane directly in front of the first left-turn vehicle waiting to turn. Calgary Transit has installed both types of left-turn gates.
- Four-quadrant gates—From the review of a variety of gates conducted in the FTA study, full-closure, four-quadrant crossing gates were selected as the best option as they offered a number of advantages over the other gate systems reviewed. A full-closure, four-quadrant crossing gate system was installed in October 1998 at the 124th Street intersection in south central Los Angeles to deter motorists from making left turns around lowered railroad crossing gates. During the experimental phase, data recorded for the first 6 months of operation at the 124th Street intersection showed that the four-quadrant gate approach resulted in a 94% reduction in the number of risky moves by motorists using the intersection. The use of four-quadrant gates has continued in Los Angeles and they have continued to have success with this countermeasure. Four-quadrant gates are effective in semi-exclusive rights-of-way, but not for street operations.

### Knock-Down Bollards

Coifman and Bertini (*3*) note that at a typical median LRT crossing with left-turn pocket lanes, the left-turn lanes are often separated from the trackway by a narrow curb, which may end before the intersection to allow for installation of and passage for a pedestrian crosswalk. With the end of this curb at the crosswalk, motorists frequently enter the LRV dynamic envelope during their left turns. The problem is compounded when drivers cross the stop bar and stop at the near side of the crosswalk. In these situations, knock-down bollards can provide a safe and effective means for restricting automobile movements in the crosswalk, effectively reducing the length of the potential LRV–motor vehicle collision zone.

### Raised Medians or Delineators

In side-running, semi-exclusive alignments, raised medians or delineators can be installed to deter left-turn motorists from driving around lowered automatic gates during their turns. In this application, the raised medians or delineators are installed on the cross street, perpendicular to the tracks, between the trackway and the intersection.

TABLE 3
COUNTERMEASURES USED BY TRANSIT AGENCIES TO MITIGATE COLLISIONS BETWEEN LRVS AND MOTOR VEHICLES AT SIGNALIZED INTERSECTIONS

| Category | Countermeasure[1] | Agency Example(s)[2] |
|---|---|---|
| Physical Barriers | Gates (left-turn gates, four-quadrant gates) | Calgary Transit, LACMTA |
| | Knock-down bollards | DART |
| | Raised medians/delineators | TriMet, DART, NFTA (Buffalo) |
| | Retractable delineators/barriers | Michigan DOT |
| Traffic Signs | Active train-approaching warning signs | TriMet, DART, LACMTA |
| | Active turn-prohibition signs | Houston METRO, TriMet |
| | Overhead lane-use control signs | LACMTA |
| | Use and placement of static signs | Sacramento RT, TriMet |
| | 2nd train coming warning sign | Maryland MTA |
| Signal Displays | Red left-turn arrows | Denver RTD, TriMet |
| | Green arrow aspects for through traffic | New Jersey Transit, TriMet |
| | In-roadway lights | Houston METRO |
| | Programmable visibility signal heads | TriMet |
| | LRT signals with format and color different from traffic signals | LACTMTA, Santa Clara VTA |
| | Far-side LRV signals | TriMet |
| Traffic Signal Phasing | All-red traffic signal phase | LACMTA |
| | Lagging left turns | LACMTA, TriMet |
| | LRV q ueue jump" or "head start" | Utah |
| | Signal pre-emption phasing | TriMet |
| Pavement Markings/Treatments | Contrasting pavement treatments | Houston METRO |
| | Crosshatch pavement markings | New Jersey Transit |
| | Lane-use markings (arrows) | San Francisco MUNI |
| | Extending/repositioning pavement treatments/markings | Denver RTD |
| Public Outreach/Education | Public outreach materials | LACMTA, Denver RTD |
| | State driver's license handbooks | California |
| Enforcement | Police presence | LACMTA, Houston METRO |
| | Photo enforcement | LACMTA |
| Other | Lower train speeds | TriMet |
| | Train-mounted cameras | Sacramento RT, Houston METRO |
| | LRV operator defensive driving | New Jersey Transit, San Diego Metropolitan Transit System |

[1]These countermeasures may not be applicable in all situations, such as emergency or reverse-running operations.

[2]The agencies noted are just a few examples of those using the countermeasures. Therefore, the use of the countermeasures is not necessarily limited to the agencies listed here.

### Retractable Delineators or Barriers

Retractable delineators can be installed to block unwanted vehicular movements in a number of applications and could be particularly useful where there is insufficient space for the installation of gates. The Los Angeles Department of Transportation (DOT) has investigated the use of retractable delineators to block traffic making left turns across the Long Beach Blue Line tracks at certain signalized intersections. Discussions between the Los Angeles DOT and a supplier in the early 2000s concluded that the particular retractable delineators available at that time could not be used for the left-turn barrier application as they would not be able to perform the number of daily "up and down" cycles required (more than 200/day) at the crossing (*8*).

Several other agencies have explored retractable delineators or barriers since that time. METRO in Houston is currently testing another type of retractable delineator for use in keeping motorists out of the shared LRV–left-turn lane when trains are approaching. The Michigan DOT, FRA, and Norfolk Southern Railway, in cooperation with


FIGURE 2 Retractable barriers under test in Wayne County, Michigan (*Courtesy:* Michigan Department of Transportation).

the FHWA, are currently testing a type of retractable barrier to discourage drivers from driving around the crossing gates at a crossing in Wayne County (*9*). The delineators are activated by a signal from the crossing gate system and reach their full deployment in about 6 s (Figure 2). Metro in Los Angeles is interested in the possible trial application of these same retractable barriers across the far side of the marked crosswalk to block the left-turn pocket lane. Los Angeles noted a number of potential issues with this application, including interaction of the delineators with pedestrians in the crosswalk, vehicles encroaching into the crosswalk, life expectancy of the delineators with the number of up-and-down cycles required for light rail operations, and failure of the delineators.

## TRAFFIC SIGNS

McCormick and Sanders (cited in reference *3*) noted that most linguistic research indicates that active, affirmative statements generally are easier to understand than passive or negative statements. In addition, Whitaker and Stacey (cited in reference *3*) found that permissive stimuli (e.g., "do") produced faster responses than prohibitive stimuli (e.g., "do not"). In the *METRORail Traffic Safety Assessment* (*4*), it was noted that the traffic control devices in use placed an emphasis on prohibited rather than permitted movements and the possibility of driver confusion about where turns were allowed and where through movements were the only permitted movements. The recommendation to METRO was displaying permitted movements provides positive guidance, which could ease decision load on drivers and could result in fewer last-second decisions in complex driving conditions. Specific recommendations for signage included

- Overhead lane-use control signs in place of extra turn-prohibition signs; and
- (Turn) ONLY signs where there was only one permitted movement at an intersection.

### Active Train-Approaching Warning Signs

Active train-approaching warning signs supplement the turn arrow signal indication, which serves as the primary regulatory control device at the intersection. These active signs warn motorists of the increased risk associated with violating the turn arrow signal indication (*1*). Transit agencies have implemented a variety of active "train-approaching" warning signs, ranging from the use of pedestrian heads that display the words, "TRAIN" or "TRAIN COMING," to the use of the W10-7 (Light Rail Transit Approaching) LRV-activated flashing blank-out signs suggested in the *Manual on Uniform Traffic Control Devices for Streets and Highways* (*MUTCD)* (*10*) (Figures 3 through 5). LACMTA uses the *MUTCD* sign, but supplements the LRV icon with the word "TRAIN" (Figure 6).

In most applications, the icon sign flashes to draw more attention from motorists. Some agencies even use a variation of the orientation of the LRV icon depending on which approach the sign is targeting. For example, in Portland (Oregon), motorists in the left-turn pocket lanes see an icon portraying the front of an LRV, whereas motorists on the cross-street approach to the tracks see an icon portraying the side or profile view of an LRV. The orientation of the LRV icon is meant to provide additional directional information to the motorists. At some agencies, these signs have evolved over the years depending on current practice and available funding. Many transit agencies, including TriMet, Houston METRO, and LACMTA have found these signs to be an effective means

FIGURE 3 *MUTCD* W10-7 (Light Rail Transit Approaching) sign.

FIGURE 4 Train-activated warning sign—Hiawatha Line, Minneapolis (*Courtesy:* Calvin Henry-Cotnam).


FIGURE 6 Train-activated warning sign in Los Angeles.

of reducing left-turn collisions. Newer LRT systems have benefited from the use of these signs by older LRT systems and have incorporated the latest technology into their systems' designs.

Active turn-prohibition signs are generally used where left and right turns are permitted across the tracks except when an LRV is approaching. Transit agencies have implemented a variety of active turn-prohibition signs, ranging from the use of pedestrian heads to display the words, "No Left Turn," to the use of the "No Right/Left Turn Across Tracks" activated blank-out signs suggested in the *MUTCD* (R3-1a, R3-2a signs shown in Figure 7) (*10*). To restrict turns when an LRV is approaching, some agencies use the activated blank-out versions of the *MUTCD* no right- or left-turn symbol sign (R3-1/R3-2) shown in Figure 8, as was recommended in *TCRP Report 17* (*1*). Sacramento RT formerly used activated blank-out signs with the words, "No Left/Right Turn." Currently they use the activated blank-out versions of the R3-1 and R3-2 symbol signs, as shown in Figure 9, which they believe work better than the text versions of the signs. METRO in Houston uses no right- or left-turn activated blank-out symbol signs that incorporate the tracks symbol, as illustrated in Figures 10 and 11.

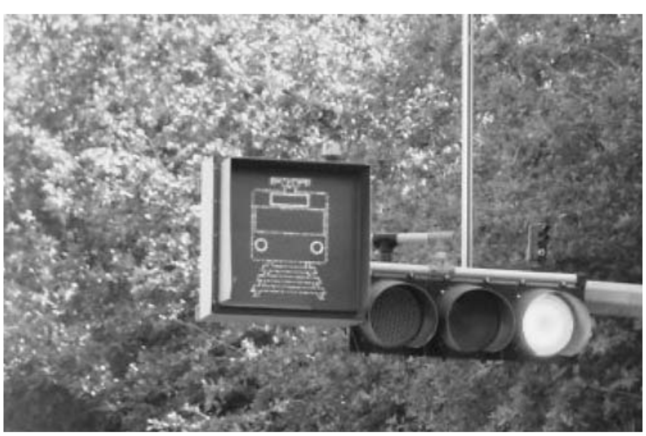

FIGURE 5 Train-activated warning sign in Houston.


FIGURE 7 *MUTCD* R3-1a and R3-2a signs.

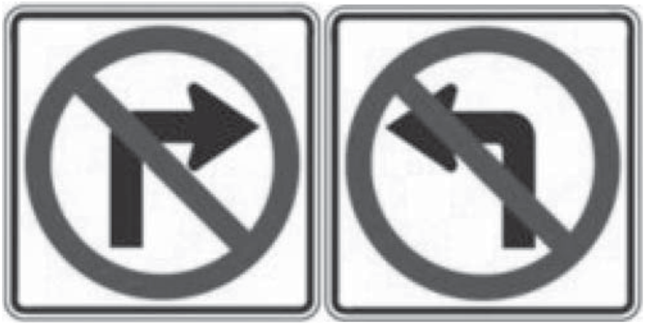

FIGURE 8 *MUTCD* R3-1 and R3-2 signs.


FIGURE 9 No right-turn activated blank-out sign in Sacramento (*Courtesy:* Sacramento Regional Transit District).

FIGURE 10 No left-/right-turn-activated blank-out signs with tracks symbol (*Courtesy:* Metropolitan Transit Authority of Harris County, Texas).

FIGURE 11 No right-turn-activated blank-out sign with tracks symbol in Houston.

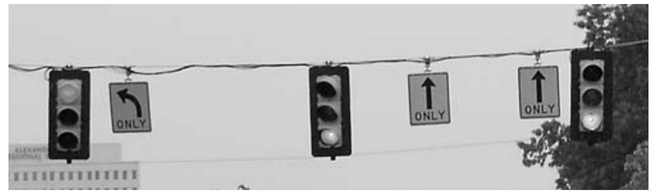


FIGURE 12 *MUTCD* overhead lane-use control signs.

**Overhead Lane-Use Control Signs**

Where motorists make left turns from the wrong lane (usually in the case of mixed-use operations), the use of overhead lane-use control signs can provide positive guidance and can indicate the allowable movements from each lane. The lane-use signs can be supplemented with the word ONLY when only one movement is permitted from the lane. Figure 12 shows the use of the *MUTCD* overhead lane-use control signs R3-5 (through-only) and R3-5a (left-turn only). Figure 13 shows the use of an overhead lane-use control sign in Houston, which incorporates the tracks symbol. Overhead advance intersection lane-use control signs can also be used to provide advance warning to motorists (*4*).

**Use and Placement of Static Signs**

Signalized intersections that incorporate LRT by design are complex intersections. When a multitude of signs are present at these intersections it can cause visual clutter, increase driver information processing time, and increase the potential for missing important information regarding permitted or prohibited movements and LRT presence. Consolidating traffic sign messages where possible and eliminating unnecessary redundancies can reduce the visual clutter as well as the chance of driver error (*4*). One way to reduce the number of signs placed at the intersection is to use the *MUTCD* combination "No left-turn/No U-turn" symbol sign (R3-18) instead of two separate signs (Figure 14).


FIGURE 13 Overhead lane-use control signs in Houston (*Courtesy:* Houston METRO).

FIGURE 14 Combination no left-turn and no U-turn sign (*MUTCD* R3-18 sign).

Sign placement can also help motorists focus on the information that is intended for them. For example, left- and U-turn-prohibition signs should be placed in the median, on the far-left side, or on the left side of the signal mast arm (not on the right side of the intersection). Figure 15 shows an example of the No U-turn sign placed over the far-right lane of traffic and where the combination No left-turn/No U-turn sign would be appropriate to reduce sign clutter. Likewise, right-turn-prohibition signs should only be placed on the right side of the intersection. When both right and left turns are prohibited at an intersection, the *MUTCD* No Turns sign (R3-3) can be placed on the signal mast arm (*4*) (Figure 16).

#### Second Train Coming Warning Sign

One of the most challenging aspects that the Baltimore LRT system experienced after start-up was the "second train coming" phenomenon that occurs on double track crossings. This phenomenon occurs when two trains traveling in opposite directions activate the crossing equipment within seconds of each other. If the first train has not finished crossing the intersection, the gates remain down as the second train passes through the crossing; however, if the first train has finished crossing the intersection, the presence of the second train causes the gates to come back down before reaching their full vertical position (*11*).


FIGURE 15 Example of sign clutter and misplacement.

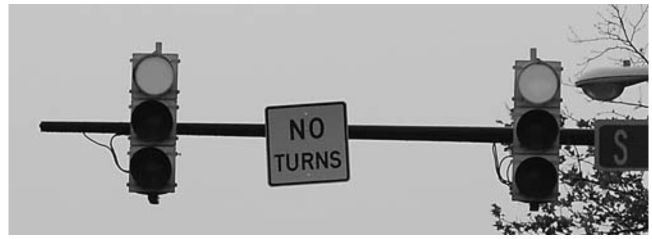


FIGURE 16 Use of the *MUTCD* No Turns sign.

As part of a demonstration project sponsored by TRB, the Maryland Mass Transit Administration (MTA) tested a second train coming warning sign. The active sign flashed the word "WARNING," which was followed by a steady appearance of the words, "2nd Train Coming," which was followed by an animation of an LRT moving through a crossing (see Figure 17). This display was supplemented with flashing beacons to attract motorists' attention to the new sign (*11*). The sign was mounted on the cantilever arm at a heavily traveled highway rail intersection where trains operate at a speed of 50 mph. Risky behaviors were observed during a period before the sign was installed and during two periods after the sign was installed. Overall, the findings demonstrated that during the second 30-day period after the sign was installed, less risky behavior was observed than during the first "after" period. A significant reduction of 26% was noted in the frequency of vehicles that crossed the tracks after the first LRV cleared the crossing while the gates were ascending but had not reached the full upward position, and before the gates descended again on activation of the circuits by the second train. However, it was still observed that the majority of drivers attempted to travel through the crossing as soon as the gates began to ascend, with or without the indication of a second train coming.

#### Left Turns Can Be Accomplished by Making Signs Showing Three Consecutive Right Turns

In addition to the signs used by transit agencies to mitigate collisions between LRVs and motor vehicles, the Texas Transportation Institute (TTI) recommended that Houston METRO make use of signs showing that left turns can be accomplished


FIGURE 17 Second train coming warning sign (*Courtesy:* Ziad Sabra, Sabra, Wang and Associates, Inc.).

by making three consecutive right turns. Along some LRT alignments, there may be few locations where left turns are permitted across the tracks, which could lead to increased pressure for motorists to turn left where left turns are possible, even if they are prohibited. Posting advanced signs showing motorists that they can accomplish upcoming left turns by making three consecutive right turns starting beyond the cross street might help reduce the number of left-turn violations. This can be iterated in public education materials by including instructions for accomplishing a left turn by making three successive right turns (*4*).

## SIGNAL DISPLAYS

### Red Left-Turn Arrows

Red left-turn arrows (as shown in Figure 18) provide more positive guidance to motorists than red balls. At a few intersections in Denver with LRT, where left turns are made from a one-way street onto another one-way street, left turns on red are not allowed owing to the LRT tracks. In RTD's experience, the red left-turn arrow signal display has worked better than the combination of a red ball and static signs stating "No Turn on Red." Motorists seem to have more respect for the red arrow signal display than the static sign, as they will violate the signs more often than the signals.

### Green Arrow Aspects for Through Traffic

In an effort to provide positive guidance, the *METRORail Traffic Safety Assessment* report recommended the use of green arrow aspects on traffic signal heads instead of green balls and redundant turn-prohibition signs (*4*) (Figures 19 and 20). Coifman and Bertini also recommend the use of green arrow aspects for through traffic to reduce the chance that a driver turning left will mistake the through traffic signals for the turning movement, which can happen for a number of reasons. First, there are generally more through signals than turn arrows. Second, the surface area of the green ball is greater than the surface area of an arrow, making it more prominent. Third, the transmittance of a green filter is greater than that of a red filter. For these reasons, the through traffic signal balls have a greater probability of being perceived by a driver than do the left-turn arrow signals (*3*). If green arrow aspects are used for through movements, a green ball should still be used in the right lane where right turns are permitted across the parallel crosswalk pedestrian movement.

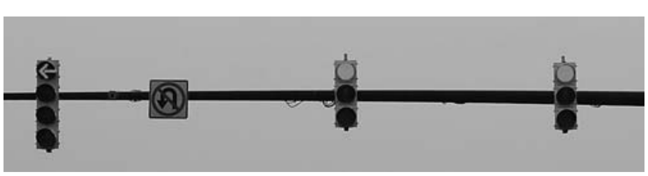

FIGURE 18 Use of a red arrow to prohibit the left-turn movement.

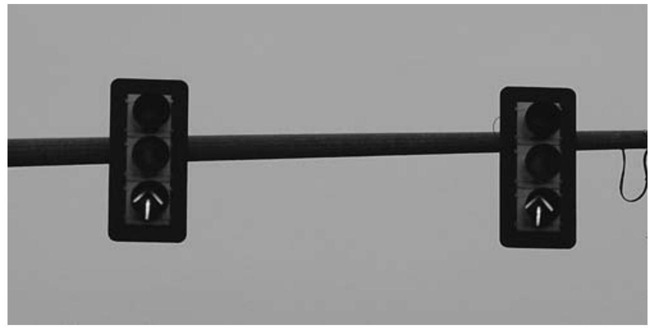

FIGURE 19 Use of green arrow aspects for through traffic.

### In-Roadway Lights

In-roadway lights are defined in the *MUTCD* (*10*) as "special types of highway traffic signals installed in the roadway surface to warn road users that they are approaching a condition on or adjacent to the roadway that might not be readily apparent and might require the road users to slow down and/or come to a stop" (*10*). In 2006, Houston METRO began testing an application of in-roadway lights to get motorists' attention to stop at the red lights on the cross-street approaches to signalized intersections with LRT and to reduce encroachment into the intersection. The lights being tested by METRO are red, installed along the stop bar, and flicker at a fast rate. An application of the in-roadway lights at one intersection in Houston is illustrated in Figure 21, as an LRV approaches from the right.

Over the past year, METRO has installed in-roadway lights at 11 intersections and experienced only two red-light running accidents at the 11 intersections since installation (the lights have been installed at the intersections on average for about 11 months). This compares with about eight red-light running accidents per year on average at these same intersections for the previous 3-year period, a reduction METRO views as significant.

Although this application was to prevent red-light running on the cross street, it could have the same effect, for some alignments, for left-turning traffic. LACMTA reported that they are currently considering using the in-roadway lights to mitigate left-turn motorist violations at intersections with LRV.


FIGURE 20 Use of arrows to control traffic movements.

FIGURE 21 In-roadway lights in Houston (*Courtesy:* METRO).

#### Programmable Visibility Signal Heads

Programmable visibility signal heads reduce the visibility of the signals from adjacent lanes. These signal heads can be used to reduce the likelihood that motorists in the left-turn lane will cue off the signals for the through traffic (*3,4*).

#### Light Rail Transit Signals with Format and Color Different from Traffic Signals

The use of LRT signals that look similar to traffic signals (e.g., colored ball, "T," or "X" signals) tend to confuse motorists (e.g., motorists may interpret a green "T" signal that is visible from a left-turn pocket as a left-turn arrow). Therefore, LRT signals should be clearly distinguishable from conventional traffic signal displays in terms of format and color and their indications should be meaningless to motorists without the provision of supplemental signs. LRT bar signals are white, monochrome bar signals that are separated in space from motor vehicle signals (*1*) (Figure 22).

FIGURE 22 LRT signals (*Courtesy:* Jon Bell).

#### Far-Side Light Rail Vehicle Signals

When LRT bar signals are placed in advance of an intersection (i.e., near-side signals), LRVs are required to stop before reaching the intersection. By installing the bar signals on the far side of the intersections and instructing LRV operators to pull up to the stop bar on a red indication, it establishes an LRV presence at the intersection and could help to reduce illegal left turns (*4*).

### TRAFFIC SIGNAL PHASING

Traffic signal phasing deals with the order in which the permitted and protected movements are allocated at signalized intersections. The following traffic signal phasing schemes have been recommended specifically to mitigate collisions between LRVs and motor vehicles.

#### All-Red Traffic Signal Phase

The all-red traffic signal phase holds all vehicular traffic on red while the LRV passes through the intersection. The purpose of the all-red phase is to discourage illegal left-turn movements across the LRV tracks by prohibiting all movements while the LRV is present at the intersection. There is evidence to suggest that motorists in the left-turn lanes may cue off of the cross-street traffic in anticipation of a leading left turn, or that they may cue off of the parallel through traffic movements or signal indications rather than focusing on the left-turn signal indication (*1,3*). By holding all traffic on red, motorists are less likely to make illegal movements across the tracks. Transit agencies including TriMet, LACMTA, and Houston METRO have implemented all-red phases at signalized intersections along their LRT alignment.

#### Lagging Left Turns

Motorists sometimes initiate their left turns as soon as the cross-street traffic receives the red, but before they receive the green arrow indication (*1*). This is particularly common at locations with leading left-turn phases, as motorists cue off the cross-street signals in anticipation of the leading left turn [Coifman and Bertini (*3*) noted that LRT accident reports suggest that this is occurring]. When the leading left-turn signal phase is pre-empted by an approaching LRV, the motorist anticipating the leading left turn could be in conflict with the LRV.

Likewise, some motorists will "sneak" through the intersection at the end of their protected turn phase. When the protected left-turn phase is a leading left turn, this can put motorists in danger of being struck by an LRV approaching during the parallel through traffic's green phase.

The use of lagging left turns can mitigate the possibility of collisions in both of these situations. Lagging left turns help remove the anticipation of making the left turn by allowing protected left turns at the end of the through green phase, rather than at the beginning. Likewise, left-turn motorists who sneak through the intersection during a lagging left-turn phase will not be in conflict with an LRV.

#### Light Rail Vehicle "Queue Jump" or "Head Start"

An LRV queue jump can be accomplished by giving LRVs a brief head start of 2 to 4 s before motor vehicle traffic after a red signal. This head start helps establish LRV presence at intersections and was recommended to Houston METRO to help prevent illegal left turns in front of LRVs (*4*).

#### Signal Pre-Emption Phasing

Transit priority that skips a normal signal phase can catch drivers by surprise. If possible, the normal sequence of signal phases should not be disrupted (*3*). This can be accomplished by returning to the phase that was pre-empted by the LRV.

### PAVEMENT MARKINGS AND/OR TREATMENTS

#### Contrasting Pavement Treatments

Contrasting pavement treatments include colored concrete, brick, etc. (Figure 23). They are used to improve the conspicuity of the tracks and to delineate the dynamic envelope of the train. Along the Metro Blue Line in Los Angeles, at locations with side-running operation, drivers on the cross-street approach to the intersection encroach into the dynamic envelope of the train. To keep drivers back, LACMTA enhanced the crosswalk before the tracks to make it more noticeable by using a colored concrete pattern. Contrasting pavements on the near and far sides of the stop bar can also be used to increase the visibility of the stop bar (*4*).

FIGURE 23 Contrasting pavement treatment in Houston (*Courtesy:* Houston METRO).

#### Crosshatch Pavement Markings

Some agencies have implemented crosshatch pavement markings at intersections to mitigate collisions between LRVs and motor vehicles. Crosshatch pavement markings are used to designate an area on the pavement where motor vehicles should not be stopped, such as on approaches to LRT tracks where drivers have a tendency to encroach on the tracks.

#### Lane-Use Markings (Arrows)

Where motorists make left turns from the wrong lane, lane-use markings can be placed in individual lanes on the approach to the intersections. By providing markings on the pavement, drivers are more likely to see them. Markings should be placed so that they are not concealed by the first one or two vehicles in the queue. The lane-use arrows can be supplemented with the word ONLY when only one movement is permitted from the lane (*4*).

#### Extending or Repositioning Pavement Treatments and Markings

To keep right-turning motorists from crossing the stop bar and encroaching into the dynamic envelope of the train, RTD in Denver extended the concrete apron of the train 8 ft into the right-turn lane, moved the stop bar 5 ft further upstream (from 15 ft to 20 ft), and applied new pavement markings. As a result of the treatments, risky behaviors by motorists decreased significantly (*7*).

#### Reducing Number of Transverse Roadway Markings

In addition to the pavement marking and/or treatment countermeasures used by transit agencies to mitigate collisions between LRVs and motor vehicles, the TTI recommended that METRO reduce the number of transverse roadway markings in certain locations. Too many transverse markings on the roadway in the vicinity of the intersection can make it difficult for motorists to distinguish one from another, such as near intersections where there is a crosswalk, stop bar, and railroad markings. Without a clear definition of the stop line, drivers may be confused as to where to stop. The number of transverse lines can be reduced by using an alternative pattern for crosswalk markings (*4*).

### PUBLIC OUTREACH AND EDUCATION

Public education plays a vital role in LRT safety in localities where the public may not be familiar with LRT operations (*4*) and, according to Coifman and Bertini (*3,* p. 10), "An education program is critical for start-up systems where drivers are unfamiliar with street railways." Recommendations for public education and outreach programs from the METRORail Traffic Safety Assessment (*4*) included

- Focusing the public education and outreach program on how and when to make left turns along the LRT line and the importance of obeying traffic regulations.
- Emphasizing in the public education program the importance of driving defensively and that traffic regulations are meant for the safety of the traveling public.
- Prominently displaying safety education materials in businesses and commercial buildings in localities along the LRT alignment that had a high rate of noncompliance with traffic regulations.
- Distributing, by location, pamphlets to passing motorists and pedestrians.

LACMTA has maintained a very active and aggressive public outreach program, which includes visiting schools, public events, churches, and businesses to give presentations and to distribute safety brochures and DVDs. Public education is also conducted through radio and television advertisements.

Metro in Phoenix is trying to boost public awareness and persuade drivers to follow traffic laws before the LRT begins servicing passengers in December 2008. Metro has put together a safety campaign based on a variety of campaigns used by other transit agencies (*12*). The safety campaign includes the following:

- A segment aimed at kids, which is being shared with schools near the transit line;
- A DVD that will be widely available and shared with traffic schools;
- Adding light rail information in the Arizona driver's manual and rail questions on the driver's test;
- Increased traffic law enforcement along the Metro line to discourage illegal turns that could result in collisions;
- Sending safety brochures to large employers or organizations near the track;
- Working with professional sports teams to show videos or present other safety information at games; and
- Providing information in English and Spanish.

#### State Driver's License Handbooks

The *California Driver Handbook* addresses LRT safety and specifically calls out the issue of left-turn accidents at intersections (*13*). The handbook states that, "Light rail vehicles have the same rights and responsibilities on public roadways as other vehicles. Although everyone must follow the same traffic laws, light rail vehicles, because of their size, require exceptional handling ability" (*13,* p. 36). It also states

> Safely share the road with light rail vehicles by:
>
> - Being aware of where light rail vehicles operate. Buildings, trees, etc., cause blind spots for the trolley operator.
> - Never turning in front of an approaching light rail vehicle.
> - Maintaining a safe distance from the light rail vehicle if it shares a street with vehicular traffic.
>
> Looking for approaching light rail vehicles before you turn across the tracks. Complete your turn only if a signal (if installed) indicates you may proceed.
>
> Light rail vehicles can interrupt traffic signals, so do not proceed until the signal light indicates you may (*13,* p. 36).

In addition, there is a diagram indicating that motorists should not turn left in front of an LRV traveling in the same direction (Figure 24).

Other states, including Texas, Colorado, Oregon, and Arizona, have also incorporated LRT education material into their driver's license manuals.

### ENFORCEMENT

Most accidents appear to be the result of traffic violations and driver error; therefore, there is a need for a strong program of enforcement of traffic regulations. Enforcement should reduce the frequency of violations and resulting conflicts and collisions with LRVs (*4*).

#### Police Presence

Assigning police to locations where violations frequently occur will help remind drivers to obey traffic regulations. Publicizing the enforcement program will encourage drivers to take traffic regulations more seriously (*4*). As part of a demonstration project in the mid-1990s, LACMTA assigned sheriff's deputies to enforce grade crossing safety along the

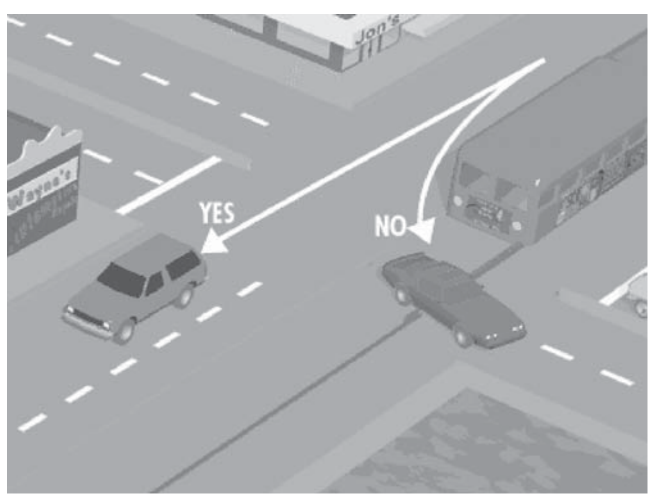


FIGURE 24 Diagram from *California Driver Handbook* (*Source:* California Department of Motor Vehicles 2008).

FIGURE 25 Photo enforcement camera (*Courtesy:* Los Angeles County MTA).

Metro Blue Line, and they continue their police presence today. Law enforcement in Los Angeles coordinated a joint Safety Awareness and Enforcement Operation at some of the busiest Metro Blue Line rail crossings to take place on a weekday morning. Deputies from Metro Transit Services Bureau, the Los Angeles Police Department, the Long Beach Police Department, and Los Angeles County Sheriff's Department conducted traffic enforcement operations and distributed safety tip handouts to both motorists and pedestrians. LACMTA organized the multi-jurisdictional committee of law enforcement. Although the primary thrust of the operation was safety education, law enforcement did issue citations to members of the public who flagrantly violated traffic safety rules (*14*).

#### Photo Enforcement

In an effort to reduce risky behaviors such as driving around crossing gates and running red lights, LACMTA has successfully used photo enforcement at both gated and non-gated crossings. Along the Metro Blue Line, LACMTA uses photo enforcement to cite drivers for running red left-turn arrows and, as a result, accidents caused by motorists making illegal left turns have been reduced by 62% since left-turn enforcement began in 2004 (*15*) (Figure 25).

### OTHER

#### Lower Train Speeds

TriMet began operation of their MAX Yellow Line in May 2004 with trains operating at 30 mph, as opposed to 35 mph. Although they originally had plans to raise the speed to 35 mph, they have not yet seen a reason to do so. In more than 3 years of operation, they have only experienced 11 left-turn collisions, which have been widely distributed across the many crossings along the corridor, and are believed to be the result of in part to the lower operating speeds.

#### Train-Mounted Cameras

Several agencies, including Houston METRO, Sacramento RT, and LACMTA have train-mounted cameras that are positioned outward. Figure 26 shows Sacramento RT's train-mounted


FIGURE 26 Sacramento RT's train-mounted camera (*left*) and view from camera (*right*) (*Courtesy:* Sacramento Regional Transit District).


FIGURE 27 Houston METRO's train-mounted camera (*left*) and view from camera (*right*) (*Courtesy:* Houston METRO).

camera. In the photograph on the left, the camera is positioned in the center of the front windshield of the train just above the windshield wiper. The photograph on the right shows the view captured by the camera from the train. Figure 27 shows Houston METRO's train-mounted camera. In the photograph on the left, the camera is positioned on the exterior front-right of the train. The photograph on the right shows the view captured by the camera from the train. These cameras have been helpful in reviewing collisions to determine causes, which can in turn help agencies identify appropriate mitigation strategies to reduce collisions.

#### Light Rail Vehicle Operator Defensive Driving

Although LRVs cannot be steered like motor vehicles and have a much greater stopping distance than motor vehicles, several transit agencies have incorporated the concepts of motor vehicle defensive driving as part of their new and recurrent operator instruction. The concepts focus on LRV operators maintaining an awareness of their surroundings through looking well ahead of the LRV's direction of travel, by scanning from curb face to curb face, and continuous movement of the eyes.

#### Standardized Crossings

*TCRP Report 17* recommends that LRT crossings be standardized throughout the system (*1*). Coifman and Bertini (*3*) point out that at many LRT crossings the traffic signal is the only control device to keep drivers out of harm's way. Therefore, every effort should be made to standardize LRT crossings throughout LRT systems, and if possible, between LRT systems.

CHAPTER FOUR

# CASE STUDIES

This chapter presents, through case studies, detailed information about the operating environment, collision history, and countermeasures tested and/or implemented for mitigating collisions between LRVs and motor vehicles at signalized intersections at a variety of transit agencies. The case studies are based on a review of the recent relevant literature and structured telephone interviews with selected transit agencies.

## TRI-COUNTY METROPOLITAN TRANSPORTATION DISTRICT OF OREGON—MAX LIGHT RAIL

TriMet began operation of their 15-mile Eastside MAX Blue light rail line in September 1986, which was among the first light rail systems in the nation. Since then, they have expanded tracks by adding 18 miles in 1998, 5.5 miles in 2001, and 5.8 miles in 2004 for a total of 44 miles.

### Collision History

When TriMet designed the system, they assumed it would operate like a street car system; however, they realized their design of the train into the streets was different than that of a street car system. The assumption was that the "little red ball" on the traffic signal would sufficiently deter motorists from making maneuvers in conflict with LRT operations, but that assumption was incorrect. They found that left-turn drivers in particular seemed to lose attention on the traffic signal controlling the left-turn movement and instead seemed to be responding to other cues like the pedestrian signals and the traffic signals controlling the parallel through movement. Early on in their operations they had problems with left-turn collisions, and therefore, have made improvements that have helped control the left-turn collisions to some extent. Over the past 6 to 7 years they have experienced about a 50–50 split between left-turn collisions and right-angle collisions caused by motorists running red lights on the cross-street approaches.

### Countermeasures

TriMet does not necessarily believe that all of the motorists violating the traffic signals are doing so deliberately, but simply not paying as much attention as needed at intersections. TriMet's goal has been to capture motorists' attention. To do so, TriMet's response to the left-turn problem was to duplicate the left-turn traffic signals at select locations. Left-turn traffic signals were placed on the far side of the intersection within median strips. Although a quantitative study was not performed, the results were not as effective as was originally hoped. Desiring to find a solution to the problem, TriMet tested the use and effectiveness of LRV-activated train-approaching warning signs, which have gone through several generations since its introduction a few years ago. The signs first started with the word "Train," which flashed when a train approached the intersection. Next they used a flashing sign displaying the words, "Train Coming." Now they use a sign with an icon of an LRV with the word "Warning." The orientation of the LRV icon depends on the direction of the train with regard to the motorists. For left-turning motorists, the icon is the front of an LRV to indicate that the train is approaching from the same direction; the icon for the cross-street traffic is the side or profile of an LRV to indicate that it is approaching at a 90-degree angle. According to TriMet, the LRV-activated train-approaching warning signs have been effective at reducing left-turn collisions. As an example of their effectiveness in Portland, in 2004 when TriMet opened the Interstate MAX Yellow Line that crosses through many signalized intersections, they established criteria for putting in the LRV-activated train-approaching warning signs. The criteria included factors such as speed, volume, school zones, crossing geometry, and sight lines. TriMet got the city of Portland to join in the effort and to use the signs liberally. As a result, they have experienced very few left-turn collisions since opening the MAX Yellow Line.

The city of Portland has accepted the use of the LRV-activated train-approaching warning for left turns as standard practice; however, the city has not installed many of these signs for the cross-street traffic. This could in part explain the shift from a majority of left-turn collisions initially to the 50–50 split between left-turn collisions and right-angle collisions.

Other effective countermeasures that TriMet has implemented to mitigate collisions between LRVs and motor vehicles at signalized intersections include

- All-red phase. Washington County implemented an all-red phase that holds all traffic approaches in a stopped position while the train passes through the intersection.
- Lower train speed. Along the Interstate Max Yellow Line, TriMet initially started operations with a train speed of 30 mph as opposed to 35 mph. Although they originally had plans to raise the speed to 35 mph, they have not yet seen a reason to do so. The city of Portland followed

suit by lowering the speed limit on the adjacent roadway to 30 mph. Since the beginning of operation, they have only experienced 11 left-turn collisions, which have been widely distributed across the many crossings along the corridor (there has not been more than one left-turn collision at any one intersection).

- Signal pre-emption phasing. Initially, after an LRV pre-empted a signal, the signal would go back to the "start," which was a green for the cross-street traffic. In the case that the protected left-turn phase was pre-empted, this phase would be skipped and motorists turning left would have to wait through another cycle. When the protected left-turn phase is skipped, some motorists may think that the signal has failed and then make the decision to violate the signal. In response, TriMet tested software that would return the signal to the phase that was pre-empted. Although this appeared to work, its use has not been well institutionalized across TriMet's light rail system.
- Increasing permissible traffic movements. Prior to the LRT line, motorists were allowed to make permissive left turns at Morrison Street in downtown Portland. During the start-up phase of the LRT line, left turns were prohibited at Morrison Street; however, they were still allowed after an all-red phase on Yamhill Street, which runs parallel to Morrison Street. During the first year of operation, there were no collisions on Yamhill Street, despite the permissive left turns, although there were several collisions on Morrison Street. Morrison was therefore changed to permit left turns in the same manner as Yamhill and both collisions and near-miss incidents decreased considerably (*4*).
- Public education. Five to 6 years ago, TriMet worked to add nearly a page of language to the state driver's manual that specifically related to driving around LRT vehicles.

As a result of their efforts, TriMet has significantly reduced their collision occurrence. On average, in the 4-year period between 1994 and 1997, TriMet experienced one collision every 33,368 train-miles. (Collisions include every incident of contact, including minor fender benders, clipped mirrors, and many other incidents in which no injuries were reported and material damage was minimal.) On average, in the 4-year period between 2004 and 2007, they experienced one collision every 93,492 miles.

## DENVER REGIONAL TRANSPORTATION DISTRICT

RTD began their LRT operation in 1994 with the 5.3-mile Central Corridor. Since then, they have expanded by adding 8 miles in 2000, 1.8 miles in 2001, and 19 miles in 2006, for a total of about 34 miles of track. RTD's street-running operations run from about 10th and Osage south of downtown Denver into and around downtown. Within the street-running section, there are approximately 35 intersections, including driveways. Along California and Stout, the LRT runs contra flow to two lanes of one-way automobile traffic. The track is separated by a 4-in. to 6-in. mountable curb. Downtown, most of the intersections have static signs. In the 1.8-mile Central Platte Valley spur, there are a few gate-protected crossings.

### High Collision Locations

RTD's collision experience has been concentrated generally in a few locations. The high collision locations are discussed in more detail here.

#### *Colfax Avenue and 7th Street*

The intersection of Colfax and 7th Street carries high volumes of automobile traffic. Colfax is a six-lane major arterial, and 7th Street leads into the Auraria Higher Education Center. It is also a complicated intersection from a geometric perspective, as 7th Street intersects Colfax on a slight curve from the north. There is a left-turn pocket lane for motorists turning left from Colfax onto 7th Street. The left turn operates with protected-permitted phasing owing to the traffic volumes at the intersection.

At this intersection, RTD experiences collisions between motorists making left turns from Colfax onto 7th Street and LRVs approaching from behind, between motorists making right turns from Colfax onto 7th Street and LRVs approaching from behind, and between motorists making right turns from 7th Street onto Colfax and LRVs approaching from either direction. RTD believes that the primary reasons why collisions occur at this intersection are that it is a complicated, busy intersection and that motorists are either not paying enough attention or they do not understand why they are not allowed to turn.

To control permissive right turns at this location, RTD used static "No Right Turn When Flashing" signs associated with a flashing yellow light (Figure 28); however, this did not work well. Drivers did not know why they were not allowed to turn


FIGURE 28 No Right Turn When Flashing sign from Colfax Avenue to 7th Street in Denver.

when the globe was flashing, so they turned anyway and some were struck by LRVs. RTD has replaced these signs with LRV-activated turn-prohibition signs (Figure 29), which activate when turns are prohibited, and these signs work better at controlling right turns than the flashing yellow. However, there are still drivers who violate the signs. RTD plans to add the LRV-activated train-approaching warning signs to provide additional information to drivers about why they are not allowed to turn.

In response to right-turn motorists exhibiting risky behaviors, including violating the active "No Right Turn" sign on the 7th Street approach at this intersection, RTD and the University of Colorado, Denver, conducted a study (*7*). In an attempt to reduce risky behaviors by motorists, they implemented three treatments, which included

- Extending the concrete apron 8 ft further in the right-turn lane, which created a visual contrast of the roadway surface to help approaching motorists identify the LRT–roadway crossing;
- Moving the stop bar on the 7th Street approach 5 ft further upstream (from 15 ft upstream to 20 ft upstream); and.
- Re-applying all pavement markings.

The researchers defined several categories of risky behaviors or "traffic violations," including stopping 2 to 4 ft past the stop bar, stopping 6 ft past the stop bar, maneuvering before the track, stopping within 4 to 6 ft of the near rail, not stopping at the flashing no turn sign, and reversing on the tracks. A before-and-after analysis revealed a significant decrease in total risky behaviors by motorists after the treatments were installed.

*Speer Boulevard and Stout Street*

The intersection of Speer and Stout is unique. Speer is an eight-lane major arterial. The two directions are separated by a creek; thus, Speer operates like a one-way pair. Stout is a one-way street running northbound into downtown Denver.


FIGURE 29 LRV-activated turn prohibition signs—7th Street to Colfax Avenue in Denver.

The LRT runs parallel to Stout. At this intersection (effectively two intersections), collisions occur between motorists traveling eastbound and westbound on Speer by running the red lights and colliding with the LRVs at a right-angle, and collisions between motorists making left turns from eastbound Speer onto northbound Stout.

Left turns from Stout onto westbound Speer (i.e., one-way northbound to one-way westbound) and left turns from Speer onto Stout (i.e., one-way eastbound to one-way northbound) are not permitted on red, as motorists must cross the LRT tracks when turning left. Left turns are allowed only during the protected left-turn signal phase; left turns are prohibited at all other times with the use of red arrow signal displays and a sign reading "Left on Green Arrow Only." In RTD's experience, the red arrow signal displays work better than red balls and "No Turn on Red" signs. Motorists have more respect for the red arrow signal displays than the static signs, as they will violate the signs more often than the signals.

*Welton Corridor*

The Welton corridor is along the D Line north of downtown. Welton is a one-way street running northbound. There is a short section of single track that runs bi-directionally. There are a couple of intersections with traffic signals. At these locations, RTD experiences collisions between motorists approaching Welton from the east who must cross the track before entering the intersection at Welton. Motorists making right turns on red will encroach on the tracks to look to the left for a gap in traffic and then get struck by an LRV approaching from the right. At these intersections, there is a sign that reads, "Train Approaching When Flashing," with an associated flashing yellow light that activates when the train is approaching. This sign has been in place since the line opened. No other countermeasures have been implemented to mitigate these collisions.

**Considerations During Planning Stages**

Based on the experience at RTD, several considerations were noted for agencies in the planning stages of LRT:

- Design and engineer out the big hazards. For example, sharing the left-turn lane is confusing for motorists; they do not know when they can be in the lane and when they cannot. Even if the signage appears to be clear, it may not be.
- Prohibit movements when possible. When movements are permitted sometimes and prohibited other times, motorists get mixed messages that can lead to problems. Prohibiting movements, however, can be difficult in street-running environments where the city needs to keep traffic moving.
- Educate the public beforehand. Educating the public is critical, especially if there is part of the design that could

be an issue. If a new sign will be introduced, for example, educate the public on what it means and why it is important to respect it. RTD did a public awareness campaign regarding the contra-flow section of the LRT. Using television spots, the campaign re-educated motorists to look both ways at intersections.
- Take away movements with gates. In RTD's new LRT section, they plan to remove certain movements with the use of gates.

## METROPOLITAN TRANSIT AUTHORITY OF HARRIS COUNTY (METRO)—HOUSTON, TEXAS

In January 2004, METRO began operation of 7.5 miles of LRT, known as the Red Line, all of which are street-running. The rail line travels at grade along the surrounding streets. Most of the alignment is side-running or median-running. There is a portion of mixed-use alignment in the Texas Medical Center (TMC). In the TMC, motorists making left turns onto side streets and into garages and hospitals must share space with LRVs on the trackway to make their turns. Special signals and signage are used to indicate to drivers when they are allowed to be on the trackway to make turns. Left turns are not allowed on some parts of the alignment and are allowed only at signalized intersections on other parts of the alignment.

### Problems

Initially, the most common type of collisions that occurred between motor vehicles and METRORail vehicles involved illegal left turns by motorists. In the median-running sections of the alignment, motorists would make illegal left turns at intersections where left turns were prohibited. In TMC's mixed-use environment, drivers had difficulties understanding the layout and the traffic control, specifically where they had to make left turns from a left-turn pocket on the tracks.

More recently, METRO has seen a shift from left-turn collisions to right-angle collisions resulting from motorists running red lights on the cross-street approaches to signalized intersections with LRT.

### Mitigation Strategies

In February 2004, after just 1 month of operation, METRO requested the assistance of TTI for an analysis of the rail line's safety. A research team consisting of experts from TTI and the light rail industry reviewed the collisions and observed conditions along the rail right-of-way. After the assessment, METRO implemented a variety of countermeasures to mitigate collisions, including improving signage for motorists. As a result, they have seen a reduction in collisions of approximately 40% since the first year of operation (*16*).

On May 31, 2007, METRO released METRORail accident statistics, which showed a continuing downward trend in the number of vehicle collisions. In its first year of operation, METRORail recorded 62 accidents, 55 accidents in 2005, and 36 in 2006. As of May 31, 2007, there had been only 14 accidents in 2007 (*17*). The decline in accidents is the result of the continued implementation of the recommendations set forth by TTI. More recent changes to the system are discussed in the following sections.

#### *Active Turn Prohibition Symbol Signs with TRACK Symbol*

Originally at intersections where left turns were protected/permitted, METRO used active light-emitting diode (LED) signs that displayed the words "No Turns." Now they use active turn-prohibition symbol signs with the "Track" symbol.

#### *In-Roadway Lights*

Currently, they are experiencing problems with motorists running red lights with a resulting shift in collision types. METRORail now experiences as many or more right-angle collisions resulting from motorists running red lights on the cross street than those involving motorists making left-turns. In 2006, METRO began testing in-roadway flashing lights to get motorists' attention to stop at the red lights at signalized intersections with LRT. The lights are red, installed along the stop bar, and flicker left to right at a rapid pace.

Between May and October of 2007, METRO installed the in-roadway lights at 11 intersections along the Main Street corridor. Prior to installation of the in-roadway lights, there were about eight red-light running accidents each year at these 11 intersections for the previous 3-year period (2004 to 2006). Since installation of the in-roadway lights at the intersections on average for about 11 months, they have experienced only two red-light running accidents at the intersections.

METRO tested the in-roadway lights at two TMC intersections where left-turn vehicles must enter the trackway to turn left. The in-roadway lights were placed along the stop bar in the left-turn lane; however, they have not had the same success with the in-roadway lights in this application as they have had on the cross-street approaches. An FHWA study is expected to be completed in 2008 on the in-roadway lights.

In addition to the modified signage in the TMC, they are currently considering the use of retractable delineators to indicate to motorists when they are allowed to get onto the tracks to make a left turn. In this application, the delineators would pop up along the lane line that separates LRVs and the traffic. They are currently under trial at a maintenance facility.

In March 2004, all-red signal phasing was implemented at 12 signalized intersections along the alignment, and METRO reports that they have been effective in controlling the number of collisions.

METRO is currently planning a system expansion using the in-roadway lights and signage that have resulted in a decrease in collisions.

## LOS ANGELES COUNTY METROPOLITAN TRANSPORTATION AUTHORITY— METRO BLUE LINE

The LACMTA Metro Blue Line opened in 1990, extending 22 miles from downtown Los Angeles to downtown Long Beach. About 6.48 miles of the Metro Blue Line is street-running, the majority of which is median-running (Figure 30), with less than 1 mile of side-running operations. There are approximately 28 crossings with gates and 62 without gates, all of which are actively controlled. The trains operate at 35 mph in the street-running sections of the alignment.

### Collision History

In the 3 years from its July 1990 opening through late June 1993, LACMTA experienced 158 LRV–motor vehicle collisions at the 100 crossings on the 22-mile Blue Line. According to LACMTA, most of the collisions were caused by motorists making illegal left-hand turns into the path of moving trains, including motorists driving around gates and motorists ignoring or failing to see red "No Left Turn" signs on street-running portions of the Blue Line, where traffic signals are used instead of crossing gates. In response, LACMTA instituted its Grade Crossing Safety Improvement Program in 1992 as an effective method to discourage illegal automotive and pedestrian movements. As part of this program, LACMTA demonstrated increased police presence along the rail line; high-resolution photo enforcement systems at four crossings; a wayside horn system; illuminated signage for pedestrians and motor vehicles; standardized warning devices, signs, signals, and pavement markings for LRT; and education and public awareness programs for schools, churches, community groups, and businesses along the Metro Blue Line (*18*).


FIGURE 30 Los Angeles Metro Blue Line (*Courtesy:* Los Angeles County MTA).

As a result primarily of the photo enforcement, LACMTA has controlled collisions at gated crossings. The issues currently are LRV–motor vehicle collisions at non-gated intersections when the motorist makes an illegal left turn in front of a train traveling in the same direction. This type of collision makes up the majority of their collisions. Another scenario, which occurs less frequently, is the "two-train scenario." This scenario might occur when motorists, in the left-turn pocket, see an on-coming train and think they can beat the train through the crossing. The motorists make the left turn and are struck by a train approaching from behind.

### Mitigation Strategies

LACMTA has found all of the following strategies to be effective in mitigation collisions between LRVs and motor vehicles at signalized intersections:

- Police enforcement. During a grade crossing safety improvement program initiated by LACMTA in the mid-1990s, the Los Angeles County Sheriff's Department Transit Services Bureau established a traffic detail to provide for increased enforcement of traffic violations at grade crossings along the Metro Blue Line. Several factors, including accident experience, responses to train operator surveys, and locations with broken gate arms were analyzed to determine how best to deploy the deputies. The traffic detail deputies wrote 7,760 citations in 90 days. Based on the success of this demonstration program, the MTA continued the Sheriff's grade crossing safety detail for 2 years, resulting in the issuance of over 14,000 citations (*19*).
- Photo enforcement. LACMTA began using photo enforcement in the 1990s at gated crossings in an attempt to reduce the risky behavior of motorists driving around gates. As a result, they have controlled collisions at gated crossings. In 2004, they expanded this practice to six non-gated crossings at signalized intersections. They installed nine cameras at these six intersections along with static signs in advance of the intersections that warn drivers of the photo enforcement. Drivers are cited for running red left-turn arrows whether a train is approaching or not. As a result of LACMTA's enforcement efforts, accidents caused by motorists making illegal left turns have been reduced by 62% since left-turn enforcement began in 2004 (*15*). However, they still have drivers running red-turn arrows.
- LRV-activated train-approaching warning signs. At major intersections, LACMTA has dedicated left-turn pockets and protected left-turn phasing. In 2000, LRV-activated train-approaching warning signs for left-turning traffic at these major intersections were added at the end of the cantilever mast arm in the Los Angeles street-running segment (as shown in Figure 30). The use of the LRV-activated train-approaching warning signs was expanded to the Long Beach street-running

segment in 2004. The LRV icon flashes when the train is approaching.

- All-red signal phase. The Gold Line opened in July 2003 and runs 13.7 miles from downtown Los Angeles to Pasadena. Only about ¾ of a mile of the Gold Line is street running operations. Trains operate at 20 mph and parallel very narrow streets through a residential neighborhood. There are seven signalized intersections, all of which have an all-red phase where the parallel traffic is also held on red as the train passes through the intersection. LRV-activated train-approaching warning signs have also been installed for the cross-street traffic at these seven intersections (which is not done on the Blue Line).
- Pavement treatment. In locations with side-running operation, drivers on the cross-street approach to the intersection encroach into the dynamic envelope of the train. To keep drivers back, they enhanced the crosswalk before the tracks to make it more noticeable. They used a colored concrete pattern, which has worked well.
- Video cameras on trains. LACMTA has video cameras mounted on the windshield of the LRV pointing outward. This allows them to review collisions to determine the cause and to develop appropriate mitigation strategies.
- Public outreach and education. LACMTA has maintained a very active and aggressive public outreach program. They distribute brochures and DVDs at schools, public events, churches, and businesses. They are currently planning to produce two videos: one that addresses the issue of left-turn collisions with LRVs at signalized intersections and one that addresses the issue of pedestrian accidents with LRVs at gated crossings. They are currently waiting for funding and expect to complete the project by December 2008.

LACMTA has explored a number of other countermeasures for mitigating collisions between LRVs and motor vehicles at signalized intersections. These countermeasures include

- In-roadway lights. Recently, LACMTA has been looking at Houston's use of in-roadway lights. Although Houston has installed in-roadway lights to discourage red-light running on the cross-street approaches to signalized intersections with LRT (to reduce right-angle collisions), LACMTA is considering using in-roadway lights to discourage motorists from running red left-turn arrows from the left-turn pocket lane. LACMTA plans to speak with the city to determine if this would be possible and, if so, to develop the specifications for the lights.
- Retractable delineators. LACMTA is also awaiting the results of two different tests of retractable delineators. Houston METRO is testing retractable delineators for use in the TMC area to delineate to drivers when they are permitted to be on the tracks to make a left turn. The Michigan DOT is currently testing a type of retractable delineator to discourage drivers from driving around the crossing gates at a heavy-rail grade crossing. Again, Los Angeles is considering the use of retractable delineators along the far "limit line" for the left-turn pocket to create a physical barrier to discourage drivers from making illegal left turns. Issues they are considering include reliability, maintenance, breakage, and vandalism, as well as issues with the city that must be explored.
- Rear-view type mirrors. LACMTA looked at using rear-view type mirrors in left-turn pockets to allow left-turn drivers to view LRVs coming from behind; however, they have not used them to this point for multiple reasons. For example, there is an issue of where to put the mirrors. They must be in a position where the drivers can see in them. At the same time, there is the issue of the mirrors being hit by large trucks.

## MARYLAND TRANSIT ADMINISTRATION—CENTRAL LIGHT RAIL LINE

Deployment of *MUTCD* Light Rail Traffic Control Devices to Improve Safety at At-Grade Light Rail Crossings in Baltimore, Maryland (2005) (*20*) presents the findings of a light rail traffic safety study performed for a 1.9-mile section of the Central Light Rail Line along the Howard Street corridor in Baltimore. The primary objective of the study was to examine the effectiveness of various traffic control devices and positive guidance measures to minimize the number and severity of accidents involving light rail, buses, pedestrians, and other vehicular traffic.

The 1.9-mile section of the Central Light Rail Line along the Howard Street corridor was constructed within the existing right-of-way on Howard Street, with two parallel tracks that run along the west side of the street for the majority of its length (Figure 31). The segment includes 17 non-gated signalized intersections. The LRT alignment includes semi-exclusive type b.3 (protected by 6-in. high curbs between crossings) and type b.4 (separated by mountable curbs, striping, and/or lane designation). Originally, there was no vehicle traffic allowed along Howard Street; however, in 1997, northbound one-way vehicular traffic was added, resulting in a rise in the rate and number of reported accidents involving LRVs, motor vehicles, and pedestrians.

FIGURE 31 Baltimore's light rail (*Courtesy:* Jon Bell).

In 1999, a comprehensive assessment study of the corridor was performed. The study included a review of the existing traffic control devices, pedestrian crossings, risky behavior patterns, and analysis of accident data for a 5-year period from 1994 to 1998.

The findings of the assessment indicated that all crossings had signs that met just the minimum requirements of the *MUTCD.* Other findings included

- Inconsistencies in the selection and placement of advisory and warning signs,
- Confusing advanced W10 series signs,
- Turn restriction signs not incorporating the track symbol into the sign,
- Lack of "Do Not Stop on Tracks" (R8-8) or "Do Not Drive on Tracks" (R15-6a) regulatory signs despite a continuous problem with such illegal movements, and
- Worn pavement markings throughout the corridor.

As a result of the assessment, MTA added many new signs and new pavement markings. No major enhancements were made to any of the left-turn signal phasing nor were barriers installed at that time. However, from 1999 to 2001, following the improvements, MTA experienced a reduction in the number and rate of accidents as well as a reduction in the claims costs. Traffic and pedestrian volumes during this same time period did not change by more than 1%.

In 2002, the MTA initiated several enhancement projects at the most accident prone locations. To overcome the problem of left-turn vehicles violating the left-turn signal indication, a recommendation was made to change the left-turn signal phase from a leading left to a lagging left, thus reducing the potential for left-turning traffic to conflict with the LRVs. Other enhancements included replacing all green ball lenses with arrow lenses where applicable, replacing left-turn (R3-1) and right-turn (R3-2) prohibition signs with the R3-1 and R3-2 signs with track symbols, renewing all dynamic envelope and lane markings throughout the corridor with paint markings, installing new regulatory signs at unsignalized intersections, and adding treatments for pedestrians. At the time of study completion, MTA was planning to add R3-1a (no right turn across tracks) and R3-2a (no left turn across tracks) activated blank-out signs at five locations that had recurring right-turn and left-turn accidents.

One noted finding of the study was the need for uniformity and consistency in the application of signs and pavement markings for controlling certain types of accidents. Specifically, the delineation of the dynamic envelope proved to be a very cost-effective measure to reduce sideswipe accidents in travel sections where the travel lanes were less than 12 ft wide. In addition, the concept of a flexible barrier separation between LRVs and other vehicle traffic, although expensive, proved to be one of the most positive treatments to prohibit illegal turning movements, minimize sideswipe accidents, and reduce accident severity.

## NEW JERSEY TRANSIT

### Hudson–Bergen Light Rail

The New Jersey Transit's Hudson–Bergen Line opened in April 2000 with approximately 6 miles of track. New Jersey Transit has added track in increments since the April 2000 opening. As of February 2006, the line has a total of 20 miles of track. Eight of the 20 miles operate in an exclusive right-of-way, and 12 miles operate in a non-exclusive right-of-way (Figure 32).

In the street-running, mixed right-of-way in downtown Jersey City and other neighboring areas, the northbound track and the southbound track are separated by a median, and the southbound track shares the one-way, one-lane travelway with automobile traffic. The signals are pre-empted by the train, and the signal cycle starts as the train approaches and the cross-street traffic receives a red light. Motorists approaching intersections from the west can make only a right turn onto the one-way street. This movement is controlled with the traffic signal and a "No Turn on Red" sign. Motorists approaching intersections from the east can make only a left turn onto the one-way street, and must cross the northbound tracks to do so. This left turn is a protected-permitted movement.

For the past several years, the Hudson–Bergen Line has experienced between six and nine collisions yearly at signalized intersections (including nine in 2007). About 90% of these collisions were right-angle collisions caused by motorists (including automobiles, buses, and tractor-trailers) running red lights on the cross streets.

Only a few intersections have the LRV-activated train-approaching warning signs that flash and display the words "Light Rail." The icon shows the profile of an LRV. A few of the intersections have a painted "block" with "crosshatch" marks. These pavement markings were created when the light rail was constructed to make the motorists aware that they are in the vicinity of the light rail line, and not in response to the right-angle collisions. Personnel from the Hudson–Bergen

FIGURE 32 Hudson–Bergen alignment (*Courtesy:* Jon Bell).

Line visited the LRT systems in Los Angeles, Portland, and San Diego to observe what they were doing in terms of safety, and installed the LRV-activated train-approaching warning signs and the crosshatch pavement markings based on the practice in these cities.

#### New Jersey Transit–Newark Light Rail

New Jersey Transit's Newark Light Rail is a 6.5-mile light rail line that operates as a rapid transit link between a terminal station at Newark Broad Street Station through Newark Penn Station located in Newark (Pennsylvania Railroad Station or Penn Station–Newark) to the Grove Street Station in Bloomfield, New Jersey. The line is in an underground tunnel for 1.7 miles either at grade or depressed cut for 3.8 miles, and includes approximately 1 mile of street-running territory. The street-running territory is part of the Broad Street Extension. The extension to Broad Street Station is mixed street-running territory where automobile traffic operates parallel to the guideway, which is separated from the traffic lanes by a 6-in.-mountable granite curb. The street-running extension alignment has 14 grade and pedestrian crossings. These intersections are protected by traffic control devices that are integrated with the train control system to give priority to the LRVs and to prevent conflicting signals and unsafe vehicular movements. Each intersection is marked in accordance with the provisions of the *MUTCD* and New Jersey DOT diagnostic team recommendations.

Newark Light Rail has experienced between about two and four collisions annually at the signalized intersections. In 2007, there were two such incidents: a right-angle collision caused by motorist running a red light and one involving a motorist within the dynamic envelope of the train.

### SACRAMENTO REGIONAL TRANSIT DISTRICT

The Sacramento RT operates approximately 37 miles of light rail, which links the eastern and northeastern suburbs with downtown and South Sacramento. Approximately 29 miles of the light rail system are double track, with the remaining being single track. Sacramento RT began light rail service in 1987, expanding their system in the late 1990s, and continuing with expansions that nearly doubled their system during the 2000s. The Sacramento RT light rail system is experiencing particular issues with each of its operating environments, including side-running, shared-lane, and a pedestrian mall.

#### Collision Experience

*Side-Running Environment*

In one section of 12th Street, which runs one-way southbound, the light rail operates in a side-running environment on the east side of 12th Street. Therefore, the cross-street traffic approaching from the east must cross the tracks before entering the intersection. The intersection of 12th Street and Ahern Street is controlled by a stop sign only on the Ahern approach. Although this is an unsignalized intersection, there is a pedestrian head that displays the words "No Left Turn" when a train is approaching (Figure 33). At this intersection, some drivers pull up past the stop bar, look right for a gap in traffic, and are struck by the train coming from their left. Two primary issues are contributing to this problem. First, drivers cannot see the pedestrian head from the stop bar. Second, the pedestrian head is not timed properly with the approach of a train.

Sacramento RT has been working with the city and the engineers, and they plan to take the following steps to reduce collisions when funding becomes available:

- Add striping and pavement markings on the cross-street approach to cover approximately 15 ft from the nearest rail to delineate a zone where drivers should not be stopped.
- Reposition the signal head so that drivers can see it from the stop bar.
- Make signal timing adjustments to the "No Left Turn" sign to give motorists enough advance warning to make decisions.
- Request funding to replace current pedestrian heads that display "No Left Turn" with the activated no left-turn symbol blank-out sign.

*Mixed-Use Operations*

Sacramento RT has mixed-use operations along parts of 12th Street, which is a one-way street running into downtown Sacramento. It carries four lanes of automobile traffic, dropping lanes one-by-one into downtown, where there are two lanes. The southbound tracks share the eastern-most lane with automobile traffic, whereas the northbound train operates in its own right-of-way (Figure 34). Therefore, drivers make left turns in a shared lane with the train and turn across the tracks carrying trains in the opposing directions (Figure 35). The problem that Sacramento RT is currently experiencing is that


FIGURE 33 Ahern Street approach to 12th Street with pedestrian head train approaching warning sign (*Courtesy:* Sacramento Regional Transit District).

FIGURE 34 12th Street mixed-use right-of-way in Sacramento (*Courtesy:* Sacramento Regional Transit District).

drivers making left turns from the "#2 lane" (instead of making left turns from the lane shared with the train) are being struck by the train in the adjacent lane traveling in the same direction. There is no signage indicating lane assignments and permitted movements; however, there are pavement markings (arrows) in each lane that indicate the permitted movements. Possible issues with the pavement markings are that they have faded and, when vehicles are stopped at the light, drivers might not be able to see them. Sacramento RT has requested that the city add lane-use signs to indicate lanes and permitted movements. There is a flashing yellow associated with the outbound train, and they have not had a problem with collisions between left-turning motorists and LRVs traveling in the opposite direction.

*Pedestrian Mall*

Another location where they are experiencing problems is downtown at the intersections of 9th and 10th and O Streets. Because there is a pedestrian mall along O Street; motorists traveling along 9th and 10th streets are not allowed to make turns onto it. The traffic on 9th and 10th is controlled by traffic lights that turn red for pedestrians and for trains. They are experiencing drivers running the red lights at O Street. Generally, the drivers stop at the lights to look for pedestrians; however, when they do not see any pedestrians, some decide to run the light, not realizing a train is coming. The collision is a right-angle collision between the LRVs and the motor vehicles. In rare cases, a motorist does not stop at all and gets struck by the train in the intersection. Sacramento RT hypothesized that this may be a result of the traffic signal progression provided along 9th and 10th Streets. In other words, drivers may be expecting the lights at O Street to turn green as they are approaching; however, if the train has preempted the signal, the light will not be green as expected; therefore, motorists run the light and a collision occurs. Although they cannot confirm this, Sacramento RT suspect that this is a factor in at least some of the collisions.

## DALLAS AREA RAPID TRANSIT

DART operates more than 40 miles of light rail, most of which is located in exclusive right-of-way. Motor vehicles and LRVs are, however, controlled exclusively by traffic signals in two different environments, a median-running segment of the South Oak Cliff Line and the central business district Transitway Mall in downtown Dallas. The segment of the South Oak Cliff Line that is controlled by traffic signals is approximately 2-miles long and runs in the middle of a four-lane divided arterial (median-running). The LRT track is separated from the motor vehicle travel lanes by a raised barrier curb. There are 12 at-grade crossings in the 2-mile segment. This section was part of a system expansion in 1997. After the expansion, DART began experiencing a number of collisions between LRVs and motorists making illegal left turns across the tracks from the protected left turn. Although lead-lag left-turn operations are normally preferred to improve progression along the arterial, dual left-turn phasing was implemented to improve compliance with the left-turn restriction. Even with these

FIGURE 35 12th Street and E Street: Vehicle occupying shared lane (*left*) and LRV occupying shared lane (*right*) (*Courtesy:* Sacramento Regional Transit District).

traffic controls in place, left-turn violations continued to occur (*21*). In an effort to mitigate these left-turn violations and collisions, in 1999 DART implemented "train coming" signs at the intersections. These signs display an LRV icon and the text, "Train Coming." The signs illuminate on detection of an LRV from either direction. The signs are placed in the median on a pedestal pole directly across from the left-turn pocket lane. There is also an additional left-turn signal in this location (*21*). Since the installation of these signs, the number of collisions between LRVs and left-turning motorists has been reduced dramatically.

## VALLEY METRO (PHOENIX)

The 20-mile initial METRO light rail line is scheduled to begin operations in December 2008. The METRO system will operate at street level in a lane separated from traffic, and trains will travel primarily in the street median. When METRO construction is complete, there will be improved light-rail synchronized signals at 148 intersections. That number includes 15 new signals added to create more U-turn areas for business access (*22*).

METRO is currently testing LRVs on Washington Street between 48th and 56th Streets. During this testing, automobile traffic travels alongside the LRV that is operated at very slow speeds (*22*). METRO is working with residents, schools, and businesses in the area to ensure that they all understand the basics of light rail safety. Beginning December 3, 2007, METRO stopped using police officers to guide traffic at intersections. Instead, both LRVs and automobile traffic are being controlled by METRO's traffic management system. The new system will control all intersections on Washington Street between 44th Street and Priest Drive (*23*).

In the spring of 2008, METRO gradually began expanding its vehicle testing activities. At that time, they began a public education campaign on the safety rules for light rail with the goal of raising the awareness of rail safety and encouraging safe behaviors. METRO plans to use the communication resources of their partner cities and sought communication partnerships with the Valley's businesses, neighborhood groups, community organizations, and the news media (*24*).

To make it safer and more street-friendly, METRO's light rail design was influenced by discussions with other rail authorities and cities. Observing and researching similar light rail systems around the country proved to be invaluable in determining appropriate system enhancements for the METRO system. To improve traffic operations and to minimize common types of collisions between LRVs and motor vehicles, the following features were incorporated into the planning, design, and/or construction of the METRO light rail system (*24*):

- Protected left- and right-turn lanes. Turns across the tracks will be made only from exclusive (left- or right-turn-only) turn lanes. "Protected" signals will control left- and right-turn movements by red, amber, and green arrows, which are considered to be the safest form of turning control used by traffic engineers. Other cities tried using special "No Left-Turn" or "No Right-Turn" signs in shared lanes that activate when a train is approaching; however, based on discussions with the LRT operating systems, these signs were mostly ignored by motorists, resulting in accidents.
- Longer left-turn lanes. Left-turn storage bays will be lengthened to handle projected 2020 traffic conditions, including storage for the added U-turns that will be required to access some driveways and local streets. Adequate storage is critical to improving safety and reducing congestion caused by traffic backing into through-travel lanes.
- LRV cameras. Cameras will be installed on the Metro LRVs so that train operators can better see obscured pedestrians and obstructions. They will also be installed on the vehicle exterior for monitoring and recording traffic conditions, unsafe driving behaviors, and accidents.
- Controlled track crossings. For safety reasons, traffic will be allowed to cross the tracks only at a controlled location. Green-arrow signal indications for left turns and U-turns will replace solid-green balls. Special signing, such as the flashing LRV-activated train-approaching sign, will be installed.
- Six-in. curbs. METRO will use 6-in. curbs to separate and protect traffic from the rail guideway. Some cities use curbs, and others use concrete barriers (e.g., San Jose), paint (e.g., Salt Lake City), or traffic buttons (e.g., Houston) to delineate the dynamic envelope of the train.
- New frontage roads. Access on one-way streets will be maintained for businesses with the use of new 16-ft frontage roads when needed. Drivers will be able to enter the frontage roads at traffic signals and exit at signalized slip ramps to re-enter the main flow of traffic. New specially designed frontage roads were designed to handle large trucks and emergency access and are necessary to maintain safe business access on the one-way streets. This is the first design of its kind being used specifically for light rail applications in the United States.

CHAPTER FIVE

# CONCLUSIONS

## SUMMARY OF RESULTS

The placement of light rail transit (LRT) in the median, adjacent to an urban street, or within an urban street can lead to complex grade crossings incorporated into signalized highway intersections. These intersections have unique operating characteristics and have been proven to create problems that can lead to collisions between light rail vehicles (LRVs) and motor vehicles. Although the types of collisions that occur at these intersections tend to vary between agencies, the collisions are almost always a result of the motorists making an illegal turn in front of an approaching LRV and/or running a red signal indication. Based on a review of the most recent literature and structured telephone interviews with selected transit agencies, the most common six scenarios of LRV–motor vehicle collisions have been characterized as the following:

- Motorists in left-turn pocket lanes violate the red left-turn signal indication and collide with LRVs approaching from behind (median-running, side-running, mixed-use).
- Motorists make illegal left turns against static turn no left-turn signs (at locations where turns are prohibited) and collide with LRVs approaching from behind (median-running, mixed-use).
- Motorists violate active turn-prohibition signs and train-approaching signs in conflict with LRV operation (at locations where turns are permitted or prohibited).
- Motorists make left turns from adjacent through-only lanes instead of from the lanes shared with the LRVs (mixed-use).
- Drivers encroach on or stop on the tracks and are struck by an LRV (coming from either direction) at a right angle (side-running).
- Drivers run a red signal indication and collide with an LRV (coming from either direction) at a right angle (median-running, mixed-use, pedestrian mall).

Based on the results of a literature review and the structured telephone interviews, the possible causes of each of these six scenarios are summarized in Tables 4 through 9, and they are linked to the potential engineering countermeasures discussed in chapter three for mitigating inappropriate and risky motorist behaviors and collisions.

In addition to the engineering countermeasures specific to the different collision scenarios, public education and enforcement play a vital role in LRT safety in localities where the public may not be familiar with LRT operations or where blatant violations (such as speeding to beat the train to the crossing) are occurring. Recommendations for education and enforcement include

- Focusing public education and outreach programs on how and when to make left turns along the LRT line and the importance of obeying traffic regulations.
- Including education materials informing that left turns can be accomplished by making three right turns.
- Emphasizing in the public education program the importance of driving defensively and that traffic regulations are intended to keep the traveling public safe.
- Prominently displaying safety education materials in businesses and commercial buildings in localities along the LRT alignment having a high rate of noncompliance with traffic regulations.
- Distributing, by location, pamphlets to passing motorists and pedestrians.
- Assigning police to enforce traffic regulations, with emphasis on turn violations and running red lights.
- Keeping police officers visible to remind drivers to obey traffic regulations.
- Publicizing the enforcement program to encourage drivers to take traffic regulations more seriously.
- Considering the use of photo enforcement, which has been an effective means of improving driver compliance with control devices in Los Angeles.

## CONCLUSIONS

There are a number of different types of collisions that occur between LRVs and motor vehicles at signalized intersections. While left-turn collisions appear to make up the greatest percentage of these collisions, right-angle collisions owing to motorists running red lights on the cross street are also a problem for many agencies. The large majority of LRV–motor vehicle collisions appear to be caused by motorists making illegal maneuvers in front of LRVs. Transit agencies have approached the LRV–motor vehicle collision problem using a variety of different countermeasures, including physical barriers, traffic signs, traffic signal displays, signal phasing, pavement treatments and markings, education, and enforcement.

The most effective means of mitigating collisions between LRVs and motor vehicles at signalized intersections is to physically separate LRV and motor vehicle movements by

TABLE 4
SCENARIO: MOTORISTS IN LEFT-TURN POCKET LANES VIOLATE THE RED LEFT-TURN SIGNAL INDICATION AND COLLIDE WITH LRVS APPROACHING FROM BEHIND

| Possible Cause | Possible Engineering Countermeasures |
|---|---|
| Signs do not convey to motorists why they are not allowed to turn. | • Install LRV-activated train-approaching warning signs to provide additional information to drivers about why they are not allowed to turn and the consequences of making an illegal left turn against the traffic signal. |
| Motorists initiate their left turns against the signal as soon as the cross-street traffic receives the red (particularly common at locations with leading left-turn phases). | • Change the left-turn signal phase from a leading left to a lagging left. |
| Motorists in the left-turn lane mistake the through-traffic signals for those controlling the left-turn movement. | • Use green arrows aspects for through traffic, which provide positive guidance by clearly indicating the permitted movement.<br>• Use programmable visibility signal heads to reduce the visibility of the through-traffic signals from the left-turn lanes. |
| Motorists in the left-turn lane cue off of the movement of the through vehicles. | • Implement an all-red phase as trains pass through intersections so that no vehicular traffic is moving as the trains pass through the intersection.<br>• Use red left-turn arrow instead of red ball to provide positive guidance. |
| Motorists make left turns across the LRT right-of-way immediately after termination of their green left-turn arrow. | • Change the left-turn signal phase from a leading left to a lagging left. |
| Motorists confuse LRT signals with traffic signals. | • Use LRT bar signals. |
| Where traffic signals are pre-empted during the left-turn phase, motorists may incorrectly assume that the signal failed and violate the signal. | • Use signal system that returns to the phase that was pre-empted. |

providing exclusive rights-of-way and grade-separated crossings. In semi-exclusive rights-of-way, physical separation of LRV and vehicle movements can be accomplished through the use of full-closure or four-quadrant gate systems or through the combined use of raised medians and two-quadrant gates. This practice has been effective for many transit agencies; however, there are drawbacks to the use of gates. Often times the footprint of the gates is too big, cost can be an issue, the gates have to fit into the cityscape, and there are noise and aesthetic considerations.

In semi-exclusive and non-exclusive environments where LRVs operate at speeds of 35 mph or less and physical separation of LRV and motor vehicle movements is not practical or affordable, LRV–motor vehicle collisions must be mitigated through traffic control. Because a large number of collisions are caused by motorist error or misperception, giving motorists enough of the right information, without giving them too much information, seems to be a key factor in mitigating risky behavior and potentially collisions. Motorists need positive guidance, which can be provided through signal displays (e.g., green or red arrow aspects), signs (e.g., lane-use signs), and pavement markings (e.g., lane-use arrows). Motorists also need sufficient information to help them make the right decisions. For example, it has been proven that simply telling motorists that turns are prohibited is not always enough to keep them from doing so. Motorists' experiences at conventional intersections may have shown them that violating a "No Turn on Red" or a "No Turns" sign has little consequence. Although this may or may not be the case at conventional intersections, it almost certainly is not the case with the added complexity at intersections that incorporate LRT. Therefore, providing the extra information about why turns are prohibited (e.g., active train-approaching warning signs) should help give motorists the additional information to make the right decisions. This approach appears to have been effective for transit agencies including TriMet, Houston METRO, and DART.

Public education and enforcement are also critical elements to mitigating collisions between LRVs and motor vehicles. Police and photo enforcement have been effective approaches to mitigating risky behaviors and collisions in Los Angeles.

Despite the efforts put forth by transit agencies and city and county traffic engineering departments, collisions between LRVs and motor vehicles at signalized intersections continue to occur, and agencies continue to seek out innovative counter-

TABLE 5
SCENARIO: MOTORISTS MAKE ILLEGAL LEFT TURNS AGAINST STATIC TURN NO LEFT-TURN SIGNS AND COLLIDE WITH LRVS APPROACHING FROM BEHIND

| Possible Cause | Possible Engineering Countermeasures |
|---|---|
| There may be too few locations to make left turns across the tracks leading to increased pressure to turn left where such movements can be made, even if prohibited. | • Post advance signs showing that upcoming left turns can be accomplished by making three right turns starting beyond the cross street.<br>• Provide an all-red phase to permit LRV movement at the end of the cross-street green phase. |
| Motorists who are used to violating regulatory signs with little consequence at conventional signalized intersections need to better understand the risks of violating turn prohibitions at intersections with LRT. | • Give LRVs a brief q ueue jump" or "head start" of 2 to 4 s before motor traffic after a red signal to establish LRV presence at the intersection and to prevent illegal left turns. |
| There are too many signs at intersections. Multiple signs increase driver information processing time and increase the potential for missing important information. | • Consolidate traffic sign messages where possible, and eliminate unnecessary redundancies.<br>• Combine the "No Left Turn" and "No U-Turn" signs into the R3-18 combination symbol sign.<br>• Place left- and U-turn prohibition signs in the median, on the far-left side, or on the left side of the signal mast arm. Do not place left- or U-turn prohibition signs on the right side of the intersection.<br>• Place right-turn prohibition signs only on the right side of the intersection.<br>• When both right- and left-turns area is prohibited at an intersection, use the "No Turn" sign (R3-3) on the signal mast arm. |
| Traffic control devices place an emphasis on prohibited rather than permitted movements. Drivers may be confused about where they can make turn movements and where a through movement is the only permitted movement. | • Displaying permitted movements provides positive guidance, could ease decision load on drivers, and results in fewer last-second decisions in complex driving conditions.<br>• Use overhead lane-use control signs in place of extra turn-prohibition signs; each prohibited movement should be included at least once on turn-prohibition signs.<br>• Use (turn) ONLY signs where there is only one permitted movement at an intersection.<br>• Use green arrow aspects on traffic signal heads instead of green ball and redundant turn-prohibition signs.<br>• Provide lane-use markings in individual lanes on the approach to signalized intersections. By providing markings on the pavement, drivers are more likely to see them. Markings should be placed so that they are not concealed by the first one or two vehicles in the queue. Supplement the lane-use arrows with the word ONLY when only one movement is permitted from the lane. |

measures in an effort to further reduce the frequency and severity of these collisions.

The findings suggest the need for the following areas of research:

- Success and/or effectiveness of the countermeasures being used by agencies. Transit agencies have taken a number of approaches and implemented a variety of countermeasures to mitigate collisions between LRVs and motor vehicles at signalized intersections. Although some of these countermeasures have been more effective than others from the perspective of the agencies, there have been few empirical studies conducted to examine the effectiveness of the countermeasures in terms of driver compliance, collision frequency, or collision severity. More research is needed to better understand the effectiveness of many of the countermeasures in terms of collision mitigation and prevention.
- Use of Chapter 10 of the *Manual on Uniform Traffic Control Devices for Streets and Highways* (*MUTCD*). This research has revealed a variety of countermeasures being used by agencies to mitigate collisions between LRVs and motor vehicles at signalized intersections; however, some of the countermeasures being used are not necessarily consistent with those in Chapter 10 of the *MUTCD.* In particular, agencies are using a variety of train warning signs and no turn signs. More research is needed to better understand why agencies do not always use the warning and control devices recommended in the *MUTCD* and what impact these inconsistencies have on safety.

TABLE 6
SCENARIO: MOTORISTS VIOLATE ACTIVE TURN-PROHIBITION SIGNS AND TRAIN-APPROACHING SIGNS IN CONFLICT WITH LRV OPERATION

| Possible Cause | Possible Engineering Countermeasures |
|---|---|
| Active signs may be activated too far in advance of arrival of the LRV. | • Use train-activation system to activate train-approaching warning signs. |
| Signs may be activated too late to provide sufficient advance warning to motorists. | • Use train-activation system to activate train-approaching warning signs. |
| Motorists do not understand why the signs are on and/or why turns are prohibited. Permitting movements at some times and prohibiting them at others causes driver confusion. | • Install train-approaching warning signs.<br>• Install active TRAIN COMING educational plaque below the turn-prohibition signs.<br>• Make movement protected-only. |

TABLE 7
SCENARIO: MOTORISTS MAKE LEFT TURNS FROM ADJACENT THROUGH-ONLY LANES INSTEAD OF FROM THE LANES SHARED WITH THE LRVS

| Possible Cause | Possible Engineering Countermeasures |
|---|---|
| Drivers are confused about which lane to turn from. | • Use pavement marking arrows indicating allowable movements and ONLY (where appropriate).<br>• Use overhead lane-use signs indicating allowable movements and ONLY (where appropriate).<br>• Use a programmable left-turn signal head.<br>• Queue jump the LRV 3 to 4 s through the intersection where left turns are permitted to enable the LRV to control the intersection and block improper left turns.<br>• Install overhead advance intersection lane-use control signs (R3-8). |

TABLE 8
SCENARIO: DRIVERS ENCROACH UPON OR STOP ON THE TRACKS AND ARE STRUCK BY AN LRV AT A RIGHT ANGLE

| Issue/Problem | Possible Cause | Possible Engineering Countermeasures |
|---|---|---|
| Drivers encroach on or stop on the tracks and get hit by an LRV at a right angle. | Having too many transverse markings on the roadway in the vicinity of the intersection (e.g., crosswalk, stop line, railroad markings) can cause confusion about where to stop. | • Reduce the number of transverse lines by using an alternative pattern for crosswalk markings.<br>• Use contrasting pavements on the near and far sides of the stop bar to increase visibility of the stop bar.<br>• Where applicable, relocate pavement markings further upstream of the intersection. |
| | Motorists may not perceive the LRT tracks crossing the approach prior to the intersection. | • Improve the conspicuity of the tracks by using a contrasting pavement treatment. |
| | Motorists attempt right/left turns on red and stop on the tracks to wait for a gap in traffic as the LRV approaches. | • If applicable, relocate the stop bar further upstream of the intersection.<br>• Install crosshatch pavement markings to designate area where motorists should not be stopped. |

TABLE 9
SCENARIO: DRIVERS RUN A RED SIGNAL INDICATION AND COLLIDE WITH AN LRV AT A RIGHT ANGLE

| Issue/Problem | Possible Cause | Possible Engineering Countermeasures |
|---|---|---|
| Drivers run a red signal indication and collide with an LRV at a right angle. | Motorists are unaware an LRV is coming or speed through the intersection in an attempt to beat an approaching LRV. | • Install in-roadway lights.<br>• Install LRV-activated train-approaching warning signs on cross-street approach (showing side-view/profile of LRV). |

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# APPENDIX A

## Interview Questionnaire

### HISTORY OF LRT OPERATIONS

1. When did LRT operations begin?
2. Have there been any expansions? When? Please describe.

### OPERATING ENVIRONMENT

3. Please describe your LRT alignment(s).
4. Approximately how many signalized intersections does the LRT operate through?
5. How many intersections are controlled by crossing gates? Are they controlled by other devices?
6. Describe the signal operations at the intersections (e.g., partial-priority, priority, pre-emption)?
7. Describe the geometry of the intersections.

### LRV–MOTOR VEHICLE COLLISIONS HISTORY AT SIGNALIZED INTERSECTIONS

8. About how many LRV–motor vehicle collisions at signalized intersections does your agency experience each year? How does this compare to collision rates when the lines were first opened? How has the collision rate changed over the years [e.g., no change, major decrease after first year(s) of operation, slight decrease over years]? Essentially, describe the collision history at signalized intersections and particularly with left-turn vehicles.
9. What are the most common circumstances of LRV–motor vehicle collisions at signalized intersections?
10. What are the most common causal or contributing factors to these LRV–motor vehicle collisions?
11. Do you have any unique environmental or operating conditions that might contribute to/reduce the occurrence of these collisions? If so, please explain.

### STRATEGIES

12. How has your agency approached the problem of LRV–motor vehicle collisions at signalized intersections (e.g., research, accident reconstruction)?
13. What processes have you gone through for selecting potential strategies for mitigating these types of collisions (e.g., research, collision typing)?
14. What strategies has your agency tested/implemented to mitigate collisions between LRVs and motor vehicles at signalized intersections?
    a. Why were the strategies implemented/not implemented?
    b. Did you coordinate with any other agency during development/testing/implementation of the strategies?
        i. If so, with which agencies did you coordinate and how (e.g., city/county DOT)?
        ii. What were each agency's roles in the process?
15. Have you conducted studies to assess the effectiveness of any of these strategies? If so, please explain. If not, can you offer any anecdotal information on the effectiveness of the strategies (e.g., in terms of operator acceptance, public acceptance, reduction in claims)?
16. Can you provide general cost information for the strategies you have tested/implemented?
17. Does your state motor vehicle manual discuss driving in an LRT environment?

### RECOMMENDATIONS

18. What recommendations or advice would you give to other agencies planning or implementing LRT with regard to LRT–motor vehicle collisions at signalized intersections?
19. What recommendations or advice would you give to other agencies that are currently experiencing problems with LRT–motor vehicle collisions at signalized intersections?

# APPENDIX B

## List of Participating Transit Agencies

Tri-County Metropolitan Transportation District of Oregon (TriMet)
Denver Regional Transportation District (RTD)
Houston METRO
Los Angeles County Metropolitan Transportation Authority (LACMTA)
New Jersey Transit
Sacramento Regional Transit District (RT)
Dallas Area Rapid Transit (DART)

Abbreviations used without definitions in TRB publications:

| | |
|---|---|
| AAAE | American Association of Airport Executives |
| AASHO | American Association of State Highway Officials |
| AASHTO | American Association of State Highway and Transportation Officials |
| ACI–NA | Airports Council International–North America |
| ACRP | Airport Cooperative Research Program |
| ADA | Americans with Disabilities Act |
| APTA | American Public Transportation Association |
| ASCE | American Society of Civil Engineers |
| ASME | American Society of Mechanical Engineers |
| ASTM | American Society for Testing and Materials |
| ATA | Air Transport Association |
| ATA | American Trucking Associations |
| CTAA | Community Transportation Association of America |
| CTBSSP | Commercial Truck and Bus Safety Synthesis Program |
| DHS | Department of Homeland Security |
| DOE | Department of Energy |
| EPA | Environmental Protection Agency |
| FAA | Federal Aviation Administration |
| FHWA | Federal Highway Administration |
| FMCSA | Federal Motor Carrier Safety Administration |
| FRA | Federal Railroad Administration |
| FTA | Federal Transit Administration |
| IEEE | Institute of Electrical and Electronics Engineers |
| ISTEA | Intermodal Surface Transportation Efficiency Act of 1991 |
| ITE | Institute of Transportation Engineers |
| NASA | National Aeronautics and Space Administration |
| NASAO | National Association of State Aviation Officials |
| NCFRP | National Cooperative Freight Research Program |
| NCHRP | National Cooperative Highway Research Program |
| NHTSA | National Highway Traffic Safety Administration |
| NTSB | National Transportation Safety Board |
| SAE | Society of Automotive Engineers |
| SAFETEA-LU | Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005) |
| TCRP | Transit Cooperative Research Program |
| TEA-21 | Transportation Equity Act for the 21st Century (1998) |
| TRB | Transportation Research Board |
| TSA | Transportation Security Administration |
| U.S.DOT | United States Department of Transportation |