Track-Related Research Volume 3: Exothermic Welding of Heavy Electrical Cables to Rail -- Applicability of AREMA Track Recommended Practices for Transit Agencies

DETAILS

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TRANSIT COOPERATIVE RESEARCH PROGRAM

TCRP REPORT 71

Track-Related Research

Volume 3:

Exothermic Welding of Heavy Electrical Cables to Rail

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Applicability of AREMA Track Recommended Practices for Transit Agencies

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SUBJECT AREAS
Public Transit • Rail

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TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2004
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TRANSIT COOPERATIVE RESEARCH PROGRAM

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

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public 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 Academies, acting through the Transportation Research Board (TRB); and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

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

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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

By Christopher W. Jenks
Staff Officer
Transportation Research Board

This report includes the results of two research tasks carried out under TCRP Project D-7, "Joint Track-Related Research with the Association of American Railroads/Transportation Technology Center, Inc.":

- Exothermic Welding of Heavy Electrical Cables to Rail and
- Applicability of AREMA Track Recommended Practices for Transit Agencies.

The report should be of interest to engineers responsible for design, construction, maintenance, and operation of rail transit systems.

Over the years, a number of track-related research problem statements have been submitted for consideration in the TCRP project-selection process. In many instances, the research requested has been similar to research currently being performed for the Federal Railroad Administration (FRA) and the freight railroads by the Association of American Railroads's (AAR's) Transportation Technology Center, Inc. (TTCI), in Pueblo, Colorado. Transit track, signal, and rail vehicle experts reviewed the research being conducted by TTCI. Based on this effort, several research topics were identified where TCRP funding could be used to take advantage of research currently being performed at the TTCI for the benefit of the transit industry. Final reports on two of these efforts are presented in this publication.

EXOTHERMIC WELDING OF HEAVY ELECTRICAL CABLES TO RAIL

Copper-based, exothermic welding is widely used in railroad tracks to connect electrical cables to rail. Such welds, when properly made, can have current-carrying capacity equal to that of the conductor and usually require less maintenance than certain mechanical attachments. However, studies have shown that copper-based, exothermic welding can produce untempered martensite in high-hardenability rail steels. That finding is of special concern when heavy electrical cable is welded because the cable can be a substantial heat sink, quenching the weld and its heat-affected zones. Transit systems would like to determine if exothermic welding of heavy electrical cables to the rail web is a cause of rail defect and service rail failures.

Under TCRP Project D-7/Task 6, TTCI evaluated current practices and possible improvements to methods of connecting heavy electrical cables to rail. In performing this evaluation, TTCI conducted an industry survey of practices and problems associated with copper-based, exothermic welding of heavy cables to rail and other alternative methods for cable-to-rail connections. In addition, TTCI conducted a metallurgical examination to determine if the cable-to-rail connections introduce damage to the rail. Based on this evaluation, TTCI offered recommendations for inclusion into an industry practice for attaching heavy electrical cable to rail.

APPLICABILITY OF AREMA TRACK RECOMMENDED PRACTICES FOR TRANSIT AGENCIES

The American Railway Engineering and Maintenance-of-Way Association's (AREMA's) *Manual for Railway Engineering* and *Portfolio of Trackwork Plans* are published as recommended practices intended to serve as guidelines for the development of individual railway policies and practices. However, the current material is directed primarily toward the North American common-carrier freight railroad network.

Under TCRP Project D-7/Task 9, TTCI reviewed the applicability of current AREMA track recommended practices to rail transit operations. This report identifies areas where AREMA recommended practices may not apply to transit operations and identifies transit practices and components that are not addressed by AREMA. It is hoped that with these areas identified, future efforts can be initiated by AREMA and/or others to develop recommended practices more appropriate for use by transit agencies.

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EXOTHERMIC WELDING OF HEAVY ELECTRICAL CABLES TO RAIL

SUMMARY

Since 2001, the Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads (AAR), has studied the current practices and possible improvements for methods of connecting heavy electrical cables to rail. The project is supported by TCRP Project D-7 and includes the following efforts:

- Performing an industry survey of practices and problems associated with (1) copper-based exothermic welding of heavy cables to the rail and (2) other methods for cable-to-rail connections;
- Performing metallurgical examinations to determine whether the cable-to-rail connections introduce damage to the rail; and
- Developing a draft recommended industry practice for attaching heavy electrical cable to rail.

A five-page survey was developed and sent to 31 transit and commuter rail systems in North America. The survey concentrated on cable-to-rail connecting processes and any associated problems or concerns. Of the 31 transit and commuter rail systems surveyed, 28 provided responses to the questionnaires. All 28 of these systems have had experience using exothermic welding to connect electrical cables to rail, and 27 of them still use the process. Copper-based, exothermic welding is the predominant procedure to connect electrical cables to rail.

Eighteen of the transit systems experienced no major problems from copper-based, exothermic welds. However, some other systems have identified cable-to-rail exothermic welds as a cause for rail failures or rail defects.

Survey results indicate that copper-based, exothermic welds had generally worked well when the welds were installed properly. The existing problems appear related to

- Lack of training for standard weld installation procedures and
- Lack of pre- or postwelding heat treatments for alloy rails.

Using the information currently available to TTCI, Section 5 provides a generic "recommended practices." Additional work will be needed to formulate complete and practical industry guidelines.

Eight of the systems surveyed used mechanical connectors to bond electrical cables to rail. Two of the eight systems reported rail damage, the cause of which was determined to be loose mechanical connectors (i.e., arcing). The other six systems stated that there had been no failures that could be specifically associated with the mechanical connectors.

Three systems used mechanical connections in the past and now use welding exclusively for cable-to-rail connection. The first transit system eliminated its mechanical connector usage because of bolt hole failures and loose bolts. Comparatively, the second transit system has been using clamp connectors in place of copper-based, exothermic welding for all cable-to-rail connections since 1988 and has experienced no rail failures to date. The third system reported using gas welding as an alternative procedure to join cable to worn rail.

TTCI performed a metallurgical examination of mechanical hole drilling to the rail web at the Federal Railroad Administration's (FRA's) Facility for Accelerated Service Testing (FAST) near Pueblo, Colorado. In the experiments, $^{3}/_{4}$- and $^{3}/_{8}$-inch holes were drilled at the neutral axis of the rail in FAST track. The rail temperatures were monitored with thermocouples and viewed using a thermal camera. It was evident that there was no significant rail temperature change during the drilling, even at the edge of the hole. The rails with drilled holes, installed on the FAST track, were tested under heavy axle loads (HAL) traffic with 315,000-pound cars, with and without inserts in the holes. After 33 million gross tons (MGT) of HAL traffic, the rails were removed for laboratory examinations. The rail material adjacent to the hole was inspected visually and by using liquid penetrant; no rail damage was detected. The rail was then sectioned for tensile tests, chemical composition analyses, hardness tests, and microstructure examinations. Laboratory results showed no significant metallurgical transformation of the rail material during the drilling process except plastic deformations at the edge of the hole. It can be concluded that there is no major metallurgical damage to the rail steel during the hole-drilling process.

1 INTRODUCTION

Copper-based, exothermic welding is widely used in railroad tracks to connect electrical cables to rails. Such cable connecting welds, when properly made, may have current carrying capacity equal to that of the conductor and usually require less maintenance than certain mechanical attachments. However, studies have shown that copper-based, exothermic welding can produce untempered martensite in high-hardenability rail steels.[1] The untempered martensite is of special concern when heavy electrical cable is welded because the cable can be a substantial heat sink, quenching the weld and its heat-affected zones. Transit systems would like to determine whether exothermic welding of heavy electrical cables to the rail web is a cause of rail defect and service rail failures. TTCI has performed an industry survey and metallurgical examinations of rails with heavy electrical cables connected to them.

Current industry standards do not exist to identify the type or the extent of testing of the rail after completion of the welds, or other cable connection systems. Current documented industry practices will be used to develop recommended practices for connecting electrical cables to rails.

2 INDUSTRY SURVEY

The objective of the industry survey was to perform a review of current practices and problems associated with connecting heavy electrical cables to rail. A five-page questionnaire (Appendix A) was developed and sent to 31 transit and commuter rail systems in North America. The survey concentrated on cable-to-rail connecting processes and any associated problems or concerns. Twenty-eight transit and commuter rail systems provided responses to the questionnaires, as summarized in Appendix B.

2.1 Use of Copper-Based, Exothermic Welding

All 28 systems that responded to the survey have experience in using exothermic welding to connect electrical cables to rail, and 27 systems are still using the process. Although one system discontinued its usage, copper-based, exothermic welding is the dominant method to connect electrical cables to rails in North American transit systems.

2.2 The Rails Used in Transit Systems

According to the survey, various rail sections are used in North American transit systems—115RE is the most widely used in transit systems, followed by 100-pound rail sections (e.g., RA and RB). Other rail sections in use include Ri59, Ri60, 85CPR, 90RA, 100RA, 100RB, 104-pound sections, 105DLW, 112-pound sections, 115RC, 119RE, 128RE, 131RE, 132RE, 133RE, 136RE, 140RE, and 155PS.

The rails are of different ages and are made by various mills. Detailed information about the rail metallurgy was not included in many of the survey responses. However, alloy rails have been used in at least two of the systems. In most cases, the rails are continuously welded.

2.3 Electrical Cables Connected to Rails

The survey shows that cable sizes of 250 millicircular mils (mcm) and 500 mcm are widely used in transit systems. Other cables used in the industry include 300 mcm, 350 mcm, 650 mcm, 750 mcm, 1,000 mcm, No. 1 American Wire Gage (AWG), No. 6 AWG, No. 9 AWG, 2/0 AWG, and 4/0 AWG.

2.4 Weld Positions

Survey results show that smaller cables (e.g., 250-mcm cables) are commonly welded to the field side of the railhead, while larger cables (500 mcm or larger) are commonly welded to the rail web. However, there are exceptions for various reasons, including past experiences of rail failures perceived to be affiliated with a particular weld position. Welding on the rail base was rarely mentioned in the survey responses.

2.5 Rail Failures or Defects Caused by Copper-Based, Exothermic Welds

Eighteen systems reported no occurrence of rail failures or rail defects associated with copper-based, exothermic welds, while the other 10 systems reported that such problems had happened.

One transit system reported a frequency of 5 to 10 rail defects per year that can be directly attributed to copper-based, exothermic welding. The defects lead to web cracks. Fortunately, ultrasonic rail flaw testing identified those defects, and very few resulted in broken rail. Problems in the other nine systems were less frequent.

Eight systems experienced problems with exothermic welds at the rail web. The cable sizes for those problematic welds were mostly 500 mcm, but 250-mcm cables were also included. One transit system surveyed indicated that rail defects were caused by making double welds for 500-mcm cables (welds near to each other). Another system identified the cause of rail failure as making welds near holes in the rail web. Making welds on or close to existing thermite rail welds was also identified as a cause of rail failure. Two transit systems noticed that the problems were limited to certain older track sections, and one of them noticed that all rail failures (three to four rail fractures in 15 years) had been confined to the 104-pound girder rail used in encased portions of street trackage.

Two systems reported problems related to exothermic welds on the railhead. The cable size was 250 mcm for those welds. One system had a derailment from a rail fracture initiated from the heat-affected zones of a CADWELD exothermic weld. This system subsequently requires 250-mcm cables to be welded to the rail web wherever possible. The other system had problematic railhead welds limited to an older section of its tracks.

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[1] R.S. Johnson, "Development in the Bonding of Electrical Connections to Rails on British Railways," *Proceedings of Railroad Rail Welding Symposium,* November 29–30, 1983, Memphis, Tennessee, published by Railway Systems and Management Association, 1985.

2.6 Alternative Methods for Cable Bonding

One transit system surveyed stopped the practice of copper-based, exothermic welding in 1988. It now uses clamp connectors for all cable-to-rail connections. The transit system has experienced no rail failure in the past 14 years.

Eight systems are currently using mechanical connectors as an alternative method for bonding electrical cable to rail. Two of the eight systems reported rail damage caused by loose mechanical connectors (i.e., arcing). The other systems stated that there had been no failures that could be specifically associated with the connectors. In addition, three transit systems that used mechanical connections in the past have since eliminated them in favor of welding as the means for cable-to-rail connection. The change to welding was made after bolt hole failures and loose bolts were experienced and attributed to the mechanical connection process. Two other systems have initiated limited use of mechanical connectors for testing purposes. Another system reported using gas welding as an alternative procedure to join cable to worn rail.

3 LABORATORY TESTS

TTCI proposed that a metallurgical analysis of rail sections with heavy electrical cables exothermically welded to them be performed. However, TTCI was unable to obtain such rail sections from the transit systems and has performed a metallurgical examination of mechanical hole drilling to the rail web.

In the experiments, two ¾-inch holes and two ⅜-inch holes were drilled at the web neutral axis of a new (1999) 136RE standard rail. The rail temperatures were monitored using a thermal camera. It was evident that there was no significant rail temperature change during the drilling, even at the edge of the hole. The rails with drill holes were tested on track under heavy axle loads at the FAST facility in Pueblo, Colorado. Two of the drilled holes (No. 1 and No. 3) were filled with inserts, while the other two (No. 2 and No. 4) were tested without an insert. After 33 MGT of HAL traffic, the rails were removed from track for laboratory examinations. Visual and liquid penetrant testing was performed around the hole areas. No defects were detected around the hole locations. The rail material adjacent to the hole was sectioned for tensile tests, chemical composition analyses, hardness tests, and microstructure examinations. Laboratory results show no significant metallurgical transformation of the rail material during the drilling process except plastic deformations at the edge of the hole. It can be concluded that there was no major metallurgical damage to the rail steel during the hole-drilling process. These test results are included in Appendix C.

4 DISCUSSION

Survey results show that copper-based, exothermic welding is the predominant procedure used to connect electrical cables to rail. The results also show that it is possible to minimize rail failure or rail defects due to electrical cable connections. Eighteen of the transit systems experienced no major problems from copper-based, exothermic welds. However, cable-to-rail exothermic welds caused rail failures or rail defects in some systems.

Transit systems all use similar, if not identical, materials in the industry for copper-based, exothermic welding because the majority of these materials come from the same supplier. The survey shows many types of rails being used by transit systems. Detailed information about the rail metallurgy was not included in many of the survey responses. However, chromium alloy rail, which has a high hardenability, was used in at least two of the systems. Previous studies proved that copper-based, exothermic welds made to such high hardenability rail without preheating may result in untempered martensite in the heat-affected zones. Cracks may develop from such brittle microstructure during the postwelding cooling process or from the fatigue under the wheel load in service. The cracks can eventually lead to rail failures. Martensite formation was also found in the heat-affected zones of copper-based welds made to standard carbon rails. It is believed that heavy cables work as a significant heat sink, increasing the postwelding cooling rate of the weld and its heat-affected zones. This effect can be balanced by measures taken to reduce the postwelding cooling rate, including preheating the rail and covering the weld during cooling.

One of the two systems that had indicated using alloy rails has adopted a preheating measure and uses thermal blankets to slow the postwelding cooling process whenever cables are welded to alloy rails. Subsequent to adopting the measures, that system had only one rail failure, which was caused by a weld made on a rail thermite weld—a violation of welding procedures of the transit system.

Although copper-based, exothermic welding has been used to join electrical cables to rails for many years, there has been very limited publicly available information regarding its effect on rail metallurgy and residual stress conditions. Industry standards covering the cables and welding materials do not commonly include detailed specifications for the welding procedures. Information generated from this TCRP-sponsored effort will help the industry in reducing the number of problems related to cable-to-rail connections. A complete and authoritative industry standard for copper-based, exothermic welding procedure could be developed after a series of controlled experiments. The effect of the exothermic welds on different rail metallurgies could be individually examined, and rail samples with and without exothermic welds could be tested to identify the effect of the welds on the performance of rails. Until then, welding procedures can be formulated on the basis of experience and field trials.

5 RECOMMENDATIONS FOR COPPER-BASED, EXOTHERMIC WELDING

TTCI believes that more thorough, targeted laboratory experiments would be useful in formulating complete, detailed, and practical guidelines for making cable-to-rail welding connections. The following recommendations are provided based on information currently available to TTCI.

5.1 Welder Training and Certification

It is important to install cable-to-rail, copper-based, exothermic welds properly to preserve rail integrity and to ensure reliable electrical connections. The welders should fully understand the welding procedures before they perform the weld installation. TTCI recommends training and certification for all personnel performing cable-to-rail welding. The certification should be renewed on a periodic basis, such as every 2 years.

5.2 Selection of Weld Location

In addition to specifications in industry standards and manufacturer's recommendations, the weld location should be selected with the following considerations:

- The weld should be located at least 6 inches, preferably 12 inches or more, from any holes on the rail.
- The weld should be located at least 6 inches from any existing cable-to-rail welds, thermite rail welds (i.e., field welds), and electric flash butt rail welds (i.e., plant welds).

A major supplier of copper-based, exothermic welding products recommends that connections within the splice bars be located on the field side of the railhead, while other connections can be located on the rail web at the neutral axis.

5.3 Preparation for Welding

Follow the manufacturer's instructions in preparing the welding mold and rail surface, and note the following items:

- Before making the first weld, preheat the mold to remove moisture.
- Clean weld area on the rail to remove debris and oxidations. If a grinder is used, be sure the grinding is gentle enough to prevent metallurgical damage to the rail.
- Clean the cable end with brushes and an approved solvent.

5.4 Proper Preheating

It is highly recommended that the rail be preheated to a proper temperature range prior to welding, especially when heavy cables are welded to high-hardenability steel rail (such as alloy rail). This can help prevent the formation of brittle microstructure and quench cracks in the rail.

When cables are welded to the web, preheating can be performed by heating the side opposite to the weld area. Air/propane or oxygen/propane heaters offer uniform heating. If an oxygen/acetylene torch is used, special care must be taken to avoid concentrated heating on any part of the rail. The recommended preheating temperature ranges are 600–750°F for high-hardenability rails and 450–650°F for standard carbon rails. The welding process should start immediately following preheating. If the delay time is more than 1 minute, the temperature of the rail should be rechecked to ensure that it is still within the required range. The cable end to be welded should also be preheated to remove moisture.

5.5 Controlled Cooling for High-Hardenability Steel Rail

When a weld is made to high-hardenability rail, applying a cooling retard cap or blanket to the weld area is recommended to reduce the postwelding cooling rate of the weld and the heat-affected zones after welding.

5.6 Postwelding Examination

The weld and its heat-affected zones on the rail should be visually examined for any weld defects. A magnetic particle test or dye penetration test is recommended for the heat-affected zones on the rail. When possible, an ultrasonic test should also be performed.

6 RELATED AAR AND AREMA MANUALS FOR COPPER-BASED, EXOTHERMIC WELDING

1. *AAR Signal Manual* Part 8.1.30, "Recommended Design Criteria for Non-Propulsion Welded-Type Railhead Bonds," revised 1996.
2. *AAR Signal Manual* Part 8.1.31, "Recommended Design Criteria for Copper Based Welded-Type Propulsion Railhead Bonds," 1996.
3. *AAR Signal Manual* Part 8.1.34, "Recommended Design Criteria for Copper Based Exothermic Welding Material," 1996.
4. *AAR Signal Manual* Part 8.6.40, "Recommended Instructions for Application of Head-of-Rail Type Welded Bonds," revised 1994.
5. *AREMA Manual*, Chapter 33, Part 7, Section 3, "Specification for Welded Type Rail Head U-bonds and Extended Bonds," 1996.
6. *AREMA Manual*, Chapter 33, Part 7, Section 5, "Specification for Thermite Type Welded Rail-Head Bonds and Track Connectors," 1996.
7. *AREMA Manual,* Chapter 33, Part 7, Section 6, "Specification for Copper Thermite Welded Electrical Connections," 1996.

APPENDIX A

TRANSIT INDUSTRY SURVEY FOR CONNECTION OF ELECTRICAL CABLE TO RAIL

TCRP D-7
TRANSIT COOPERATIVE RESEARCH PROGRAM

EXOTHERMIC WELDING OF HEAVY ELECTRICAL CABLES TO RAIL QUESTIONNAIRE

1. TRANSIT AUTHORITY

Date: ______________________________

Transit Authority: ______________________________
____

Name: ______________________________

Title: ______________________________

Address: ______________________________
____
____
____
____

Telephone: ______________________________

Fax: ______________________________

E-mail: ______________________________

2. TRACK AND OPERATING DATA

Rail: Size, welded/jointed, metallurgy, date, mill

____

____

____

Bonding Cable: Size, type, voltage

____

____

____

____

Track Structure Type:

____

____

____

____

Approximate Number and Type of Bonded Rail Joints in Track: ______________________________

Maintenance & Operations:

Wheel Load: ______________________________

Traffic Density (Annual MGT): ______________________________

Maximum Operating Speed: ______________________________

Third Rail/Overhead Catenary: ______________________________

Rail Defect Detection Frequency: ______________________________

Track Ownership: ______________________________

Maintenance Responsibility: ______________________________

Light Rail/Heavy Rail Transit: ______________________________

Joint Use: ______________________________

3. EXOTHERMIC RAIL BOND WELDING—PROCESSES & PROCEDURES

Description of current exothermic rail bond welding processes and procedures, including allowable cable size, weld type, position and location, rail surface preparation, preheat/postheat requirements, allowable temperature range (ambient/rail), heat-affected zone, inspection, and quality control requirements:

4. EXOTHERMIC RAIL BOND WELDING—PROBLEMS & SAFETY CONCERNS

Description of exothermic rail bond welding problems and safety concerns. If rail failures have occurred, include information as to the location, position, type, and number for both detected internal defects and broken rail:

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Note: Please provide information as to the availability of rail failure samples that may be used for metallurgical analysis.

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5. ALTERNATIVE RAIL BONDING PROCEDURES

Description of alternative procedures now in use for bonding of heavy electrical cables to the rail (e.g., bolted connections), together with any problems and safety concerns. Details including bolt type and size, position on rail, rail surface and bolted hole preparation, allowable drill speed and temperature range, inspection and quality control requirements:

6. ADDITIONAL COMMENTS

APPENDIX B

SUMMARIES OF INDUSTRY SURVEY RESPONSES

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 1

System Details:

- Operates and maintains 28.6 track miles.
- 600-volt DC.
- Third rail traction.
- Heavy rail transit system.
- Rail weight 100 and 115 pounds, welded or bolted.

In the past, 500-mcm electrical cables were attached to the web of rail using exothermic welds. Roughly one or two defects resulting from rail damage occurred annually. The use of exothermic welds was stopped about 15 years ago; since that time, rail bond cables have been attached to the web and base of rail using a specifically designed clamp connector with excellent results. The system reported no rail damage or failures in the rail bond cables.

The 250-mcm rail bond cables were attached to the field side of the head of rail using exothermic welds. Although rail defect problems were minimal, these electrical cables are now also clamped to the web and base of rail.

Beginning in 1988, the practice of welding electrical cables to any portion of the rail was prohibited. Since that time, all 250- and 500-mcm power cables have been attached to the rail using the standard clamp connector.

Maximum Operating Speed:	40 mph
Wheel Load:	12,000 pounds
Rail Defect Detection Frequency:	Once annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 2

System Details:

- Operates and maintains 1,077 route miles.
- Light rail.
- Overhead catenary transit system.
- Rail weight varies from 90 to 149 pounds, welded or bolted.
- Open track includes timber crossties and crushed rock ballast.
- Encased track includes direct fixation systems.

The system's standards call for exothermic welding of 500- and 750-mcm power cables to the web of rail in both street (encased) and subway (open) trackage. Pre- and post-heating procedures are not required.

A very minimum number of rail failures resulting from the exothermic welding of rail bonds to the web have occurred. Total failures (approximately 3 or 4 rail fractures in the past 15 years) have been confined to the 104-pound girder rail section used in the encased portions of street trackage. This rail section is no longer used in new track construction. No failures related to exothermic rail bond welding have been found in the subway (i.e., open) trackage.

The system has recently initiated an ultrasonic rail defect detection program covering the subway trackage. The first tests were carried out in November 2000. No defects were found at rail bond exothermic rails. Plans are to re-test in about 6 months and, depending on results, implement an ultrasonic rail-testing program on a 3-year cycle.

Maximum Operating Speed:	50 mph
Wheel Load:	9,200 pounds
Rail Defect Detection Frequency:	As noted above

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 3

System Details:

- Operates and maintains 21 route miles.
- 700-volt DC third rail power.
- Heavy rail transit system.
- Rail weight 115 pounds, welded or jointed.

Head of rail installations include all C-bond connections and 250-mcm power rail joint bonds using exothermic welds. All rail-bonding cables ranging from 500 to 750 mcm are attached to the web of rail using exothermic welds. Rail preparation includes grinding, cleaning, and preheating to at least 60°F to remove all moisture.

No problems have occurred except for an occasional failed weld at the time of installation due to improper rail surface preparation. Bolted type clamp connectors have been replaced or are in the process of being replaced with exothermic welded rail bond connections to the rail web.

No broken or cracked rails have occurred. Proper rail preparation and welding procedures are essential.

Maximum Operating Speed:	58 mph
Wheel Load:	Maximum 14,500 pounds
Rail Defect Detection Frequency:	Twice annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 4

System Details:

- Operates its own commuter services and also controls commuter services operated by freight railroads over 1,189 track miles, with approximately 50 percent owned and maintained by the system and 50 percent owned and maintained by freight railroads.
- These operations include approximately 120 track miles.
- 1,500-volt DC overhead catenary power.
- Heavy rail transit.
- All other routes are diesel powered, i.e., non-electric traction heavy rail transit systems. Track structure is typically 115-pound continuous welded rail or jointed rail on timber crossties and limestone ballast.

All rail bonds are welded to the field side of the head of rail using either exothermic welds or oxygen-acetylene gas welds. Typically, the exothermic welding process is used on new and/or minimal-wear rail. Oxygen-acetylene gas welds are used to apply U-bonds on service-worn rail and in special track work.

Welding to the web of rail is not permitted. No rail damage or broken rails have resulted from either the exothermic welding process or oxygen-acetylene welding process. Gas welding is cheaper but requires pre- and postheating procedures.

Impedance bond leads are always gas welded to the field side of the railhead using a 500- or 350-mcm cable. About 800 impedance bonds are currently in track. In the past, one or two rail failures due to transverse fissures occurred annually and were attributed to incorrect gas welding procedures. Welding crews have been retrained, and the problem has been corrected.

Maximum Operating Speed:	65 mph
Wheel Load:	20,350 pounds
Rail Defect Detection Frequency:	Twice annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 5

System Details:

- Operates and maintains 320 route miles.
- Main line consists of 40 percent concrete and 60 percent timber crossties on crushed rock ballast.
- Joint operations with freight railroads use standard centralized traffic control (CTC) signal control systems.
- No electric traction power.

Track wire bonds are attached to the web of rail using exothermic welds. Signal circuit wires are attached to the field side of the head of rail using exothermic welds. No problems with either internal rail defects or resulting rail failures have been reported.

Maximum Operating Speed:	90 mph
Wheel Load:	35,750 pounds
Rail Defect Detection Frequency:	120-day intervals

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 6

System Details:

- Operates and maintains 656 track miles.
- 600-volt DC third rail power.
- Heavy rail transit.
- System has various types of track structure, including tie blocks in concrete, ballasted, and open deck with 100- and 115-pound rail, welded or jointed.

The system does not permit the exothermic bonding of 500-mcm electrical cables to any portion of the running rail. Currently, these electrical cables are attached to the rail by inserting or compressing a soft copper terminal attached to the cable into a 1$^1/_8$-inch hole drilled in the web. Loose connections and rail defects have been a problem. As a result, the connection between the rail web and the bolted cable has been under testing for over a year with very favorable results. There have been no premature failures.

Bolted rail joints are bonded with C-bonds, equivalent to 250 mcm, attached to the field side of the head of rail using exothermic welds. The bolted cable connection is being considered for testing and evaluation.

Special track work areas such as interlockers now use two 500-mcm cables attached to the web of rail with compression terminals as described above in lieu of direct welding to the crossing frog.

Maximum Operating Speed:	60 mph
Wheel Load:	17,500 pounds
Rail Defect Detection Frequency:	Four times annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 7

System Details:

- Light rail commuter system.
- Overhead 1,500-volt DC catenary power.
- Rail weight 115 RE and 100 RE continuous welded rail.
- Joint use includes both freight and passenger service.

The 300-mcm rail bonds are all installed on the field side of the head of rail using exothermic welds. Preparation for welding includes rail grinding and preheating the head of rail. Current welding procedures do not include provisions for inspection or quality control.

To date, the system has found no rail defects resulting from the rail-bonding process.

Maximum Operating Speed: 35 mph
Wheel Load: 32,875 pounds
Rail Defect Detection Frequency: Twice annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 8

System Details:

- Operates 14 route miles.
- Heavy rail transit system.
- Third rail, 600-volt DC power.
- Track structure includes 100- and 115-pound continuous welded rail encased in concrete.

The 500-mcm negative rail bonds are attached to the web of rail using exothermic welds. This practice was initiated about 10 years ago; no rail failures have occurred. Prior to that time, these bonds were connected to the rail using plugs inserted in 3/4-inch holes drilled in the web of rail. Bolt hole failures were a continuing problem.

Exothermic welding is used to attach the 250-mcm rail joint bonds to the field side of the head of rail using double-wire, Type C rail bonds 9 to 13 inches in length. These bonds are placed above the angle bar and require two exothermic welds in close proximity on either side of the rail joint. Railhead breakout has been a problem, resulting in about six failures annually, possibly due to the high heat concentration created by the double exothermic weld on the railhead.

Maximum Operating Speed: 50 mph
Wheel Load: 10,000 pounds
Rail Defect Detection Frequency: Twice annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 9

System Details:

- Operates and maintains roughly 270 route miles.
- Heavy rail transit system.
- Uses both third rail and overhead catenary power.
- Rail size varies from 119-pound to 140-pound continuous welded rail on either timber or concrete crossties.
- Joint track uses are on various segments of the system.

Both 500-mcm and 250-mcm power bonding cables are attached to either the web or the head of rail using exothermic welds. No rail defects or failures have occurred in recent years.

Signal wires are bonded to the web of rail using a plug bond inserted in a 3/8-inch diameter hole drilled at the rail neutral axis. These wires are typically 250 mcm thick. There are no rail defects or failures.

Maximum Operating Speed: 90 mph
Wheel Load: 39,375 pounds (freight: 315,000 pounds gross vehicle weight)
Rail Defect Detection Frequency: Twice annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 10

System Details:

- Operates approximately 55 track miles.
- Light rail overhead catenary system.
- Majority of the track structure consists of either timber or concrete crossties on crushed rock ballast.
- 115RE continuous welded rail.

The 250-mcm double-signal bond wires are attached to the field side of the rail head using exothermic welds. Each bond wire is approximately 8 inches long and positioned such that the outside exothermic weld is not to exceed 5 inches from the rail end. Bonds are furnished and installed in accordance with the recommended design criteria requirements of AREMA.

The 500-mcm power bonds (single or double) are attached to the web of rail by means of exothermic welding in accordance with applicable AREMA requirements.

The system uses exothermic welding procedures exclusively and has not experienced any rail failures that could be attributed to the exothermic welding of rail bonds.

Maximum Operating Speed: 55 mph
Wheel Load: 11,250 pounds
Rail Defect Detection Frequency: Once every 2 years

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 11

System Details:

- Operates 34 route miles with an annual density of 5.09 MGT.
- Light rail, overhead catenary system.
- Track structure consists of a mixture of 115RE and 132RE continuous welded rail installed on either timber or concrete crossties and crushed rock ballast.

Exothermic welding is used to attach both the 500-mcm power cables to the web of rail and the 250-mcm double-signal bond wires to the field side of the head of rail. Bonds are installed in accordance with the manufacturer's suggested specifications.

The system has not incurred any rail failures attributable to the exothermic rail bond welding procedures.

Maximum Operating Speed:	55 mph
Wheel Load:	10,132 pounds
Rail Defect Detection Frequency:	Twice annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 12

System Details:

- Owns and operates 43 route miles.
- Track structure: 115RE and 136RE continuous welded rail, with maintenance contracted out. Joint-use tracks with the freight or transit systems use standard CTC signal control systems.
- No third rail or overhead catenary electric traction power.

Signal bonding cables are No. 6 AWG attached to either the head or the web of rail using exothermic welds; no preheat or postheat requirements.

No problems have been incurred with either internal rail defects or resulting rail failures attributable to the exothermic welding procedures.

Maximum Operating Speed:	90 mph
Wheel Load:	35,750 pounds
Rail Defect Detection Frequency:	Once annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 13

System Details:

- Operates and maintains a 28-route mile of double track.
- Light rail system.
- 600-volt DC overhead catenary power.
- System has been in operation for 5 years; near-term expansion plans will provide an additional 22 route miles.
- Track structure includes 115-pound continuous welded rail (CWR) using direct fixation, ballast with concrete ties, or encased girder rail.

Power bonding includes the use of two 500-mcm or two 250-mcm 600-volt DC cables attached to the rail web using exothermic welds with at least 6 inches of spacing between welds. Signal bonds at rail joints include two 250-mcm C-bonds attached to the railhead using exothermic welding.

The system has not incurred any rail failures attributable to the exothermic rail bond welding procedures.

Maximum Operating Speed:	65 mph
Wheel Load:	9,800 pounds
Rail Defect Detection Frequency:	Once annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 14

System Details:

- Operates 40 track miles of light rail overhead catenary and 32 track miles of heavy rail transit.
- 115-pound CWR with both ballasted and direct fixation track.
- About 7 track miles of the light rail system are jointly used by the system and a freight railroad.

Current standards require that both the 500-mcm power cables and the 250-mcm signal cables be attached to the web of rail using exothermic welds. At locations requiring the equivalent of 1,000-mcm power cables, the system now specifies the use of two 500-mcm cables attached to the web of rail with the exothermic welds positioned at least 6 inches apart.

Rail clamps are used for making temporary cable bond connections—rail drilling is prohibited.

Two rail failures have occurred as a result of the exothermic welding of double 500-mcm power cable bonds due to excessive heat concentration:

- Wing rail on a No. 8 frog—light rail trackage.
- Straight running rail—heavy rail trackage.

No rail defects or resulting rail failures have occurred at either the 250-mcm signal bond connections or the 500-mcm, single-power bond connections welded to the rail web.

Maximum Operating Speed:	55 mph
Wheel Load:	10,000 pounds (transit)
Rail Defect Detection Frequency:	Once annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 15

System Details:

- Operates and maintains approximately 545 track miles providing both the system's commuter rail service and joint freight service.
- Commuter operations use overhead catenary power.
- Rail is 98 percent welded and ranges in weight from 105 pounds to 155 pounds.
- 95 percent timber and 5 percent concrete ties.
- Crushed rock ballast.

All signal and power bonding cables are attached to either the railhead or web using exothermic welds:

- No. 6 AWG Signal wire—railhead.
- 2/0 AWG Signal cable—rail web.
- 4/0 AWG Power cable—rail web.

The system has used only exothermic welds for all signal and power cable connections since 1985, and roughly 99 percent of all existing connections were replaced by 1990. Exothermic welding is now used exclusively to ensure greater system reliability. No related rail damage or failures have occurred because of exothermic welding procedures.

Maximum Operating Speed: 80 mph
Wheel Load: 15,000–35,750 pounds
Rail Defect Detection Frequency: Twice annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 16

System Details:

- Operates 64.8 route miles.
- Both light and heavy rail transit systems.
- 600-volt DC overhead catenary power.
- Track is 100- and 115-pound CWR on timber crossties and crushed rock ballast.

Power rail bonds are maximum 500-mcm cables attached to the web of the rail using exothermic welds. When a larger cable size is needed, multiple 500-mcm connections are used, with welds at least 12 inches apart. Signal cables are 250-mcm C-bonds welded to the head of the rail. No rail defects or rail failures have resulted from these exothermic welding procedures.

Maximum Operating Speed: 60 mph
Wheel Load: 14,000 pounds
Rail Defect Detection Frequency: Once every 2 years

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 17

System Details:

- Operates 13.75 route miles.
- 600-volt DC overhead catenary.
- Light rail system.
- Track is a 100-pound continuous welded rail.
- Crosstie and ballast or concrete slab with direct fixation.

The 650-mcm power cables are attached to the web of the rail using either exothermic welds or bolted connections. Typically, the welded rail bonds are located within turnouts and the bolted rail bonds are used in the main track between turnouts; in the existing track, approximately 45 percent of the rail bonds are welded and 55 percent are bolted. All 250-mcm signal bond cables are bolted to the web of the rail.

No rail failures have been reported at the welded or bolted rail bond locations.

Maximum Operating Speed: 44 mph
Wheel Load: 6,420 pounds (average)
Rail Defect Detection Frequency: Once annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 18

System Details:

- Operates about 15 route miles.
- Third rail power.
- Heavy rail transit system.
- Roughly 67 percent of the route miles are ballasted track with timber crossties, and 20 percent are timber block ties in subways; remaining trackage is on bridges and viaducts.

The system does not currently permit rail bond welding to the web of rail, but is now evaluating the potential use of exothermic welding of rail bonds to the web based on a study and investigation carried out by another transit system. Further consideration, however, is now on hold pending the results of this TCRP Project D-7 research.

The 500-mcm rail bond cables are clamped to the base of the rail. Drilling to attach rail bonds with bolts on running rails is not permitted. The C-bonds and 250-mcm cable bonds are attached to the head of the rail using the exothermic welding process.

No rail failures have occurred that may be attributed to current rail bonding procedures.

Maximum Operating Speed: 65 mph
Wheel Load: 13,750 pounds
Rail Defect Detection Frequency: Twice annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 19

System Details:

- Operates 39 route miles.
- Light rail transit system.

- Overhead catenary power.
- Track is primarily 115RE continuous welded rail.
- Concrete and timber crossties and crushed rock ballast.

Present maintenance practice provides for the exothermic welding of the 250- and 500-mcm power cables to the web of the rail. This procedure has been used exclusively and is preferred by the system's track and power maintenance personnel. No rail damage or rail failures have occurred as a result of exothermic welding to the rail web.

Currently, test sections are being considered for specific areas of new track construction. The test sections use paved double track with complex electrical circuitry. Bolted connections are to be used by attaching a power cable, equipped with cable lugs, to a threaded stud bolt welded to the web of rail. The purpose is to enhance rail and signal maintenance; however, concerns exist as to possible corrosion, loosening of the connection, and the potential for easier theft of the copper cables.

Maximum Operating Speed:	55 mph
Wheel Load:	9,000 pounds
Rail Defect Detection Frequency:	Once every 2 years

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 20

System Details:

- Operates 20 route miles.
- Light rail transit system.
- 600-volt DC overhead catenary.
- An additional 3 route miles are included in current expansion plans.
- Track structure consists of a 100-pound continuous welded rail.
- Of the route miles, 80 percent are ballasted with concrete crossties, and 20 percent are direct fixation encased in streets.

The 500-mcm cables, used for both power and signal bonds, are attached to the web of the rail using exothermic welds. Typically, two or three power cables, required for back-up protection, are installed at each location, with the exothermic welds staggered to avoid excessive heat concentration at the web of the rail. These 500-mcm multiple cable connections are used primarily to protect bonding continuity in the event of exothermic weld failures, i.e., bonding redundancy.

Because of exothermic welding of rail bonds, there occurred four rail failures, two internal defects, and two broken rails since the start of the system's operation in 1981, with the most recent failure reported in 1996.

The system is currently testing a rail bonding system as an alternative method for attaching heavy cables to the web of the rail using a mechanical (i.e., bolted) connection. These rail bond connections are to be tested in areas of special track work and in streets with direct fixation track that is subjected to excessive salt and moisture, which adversely affects corrosion of the welded rail bonds. Comparable bonding performance, installation, and maintenance will be evaluated.

Maximum Operating Speed:	50 mph
Wheel Load:	12,456 pounds
Rail Defect Detection Frequency:	Direct fixation track—once every 2 years Open track—once every 3 years

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 21

System Details:

- Operates and maintains 701 track miles, including 353 track miles with third rail.
- 750-volt DC power and 348 track miles non-electric diesel power.
- Operations provide both passenger and freight service.
- Rail weight varies from 100- to 136-pound continuous welded rail on timber or concrete crossties and crushed rock ballast.

Currently, all 500-mcm power cables are bonded to the web of rail using exothermic welds. No rail failures have occurred that can be attributed to the web bonding procedures.

Past practice required that the 250-mcm signal or power cables be bonded to the rail head with exothermic welds, except at frogs. The system has experienced resulting rail defects and rail failures emanating from the heat-affected zone of the exothermic welds in the railhead and is now initiating standards and procedures requiring the application of welded web bonds in lieu of head bonds for 250-mcm cables wherever possible.

NOTE: Although rail defect statistics specific to exothermic weld-related failures are not available, the system did have a derailment in 2000. This was caused by a rail fracture initiated at a micro-crack in an exothermic weld's heat-affected zone at the rail head. The metallurgical failure analysis concluded that ". . . the evidence suggests that the fracture of the rail was a long-term phenomenon with final fracture occurring shortly (if not immediately) before the derailment."

Maximum Operating Speed:	80 mph
Wheel Load:	32,875 pounds (freight)
Rail Defect Detection Frequency:	Twice annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 22

System Details:

- Operates 39 route miles.
- Third rail power.
- Heavy rail transit system with an additional 7 miles either under construction or proposed.
- Track includes 115 RE continuous welded rail either ballasted or direct fixation (aerial structures/subways).
- Rail is controlled cooled, heat treated or head hardened, including 29 route miles (58 track miles) of chromium alloy rail.

All bonding cables are 500 mcm attached to the rail web using exothermic welds. The welds must be at least 6 inches from a rail weld (shop or field); if possible, a 12-inch spacing is preferred. When applying exothermic welds to chromium alloy rail, specific preheating and posttempering procedures must be adhered to before and after cables are web welded.

With one exception, the system has had no rail defects or failures resulting from the use of exothermic welds at the rail web in either standard carbon or alloy rail. One broken rail occurred as a result of making an exothermic weld directly on a field weld causing a rail failure and pull-apart during the past winter season. The rail involved was a chromium alloy rail. The broken rail was not due to a process problem but rather a failure to follow installation procedures. As a followup to this incident, the system replaced several exothermic welds that did not meet the 6-inch criterion.

Maximum Operating Speed:	70 mph
Wheel Load:	10,000 pounds
Rail Defect Detection Frequency:	Four times annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 23

System Details:

- Operates and maintains 206 track miles (103 route miles).
- Third rail power.
- Heavy rail transit.
- Track includes at-grade, aerial, and tunnel structures with 115-pound standard carbon continuous welded rail.
- Curve rail is heat treated.

Current practice covering the installation of power rail bond cables includes

- 1,000-mcm cables.
- Rail base clamps.
- 500-mcm cables.
- Bolted connection to the rail web using 5/8-inch Huck compression fasteners.
- 250-mcm cables.
- Railhead bonds using a C-bond or equivalent.

The system has not experienced any defects or failures attributed to rail damage resulting from the use of rail base clamps or bolt connections.

In the past 10 years, the system has had several rail failures due to (1) exothermic welding of power bonds to the rail base, (2) exothermic welding of 250-mcm cables to the railhead at two locations, and (3) loose clamps causing arcing and resulting in rail damage at three locations. These problems occurred on older sections.

Maximum Operating Speed:	73 mph (currently regulated to 59 mph)
Wheel Load:	15,000 pounds
Rail Defect Detection Frequency:	Four times annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 24

System Details:

- Operates 70 route miles.
- Non-electric diesel power.
- Heavy rail transit.
- Track is owned by the state, maintained and dispatched by a freight railroad, and jointly used.
- Rail is 115RE and 136RE continuous welded rail on timber crossties and crushed rock ballast.
- CTC signal control system.

Signal bonding cables are No. 6 AWG attached to either the head of the rail using exothermic welds or to the web of the rail using a 3/8-inch plug-type signal bond.

No problems have been incurred with either internal rail defects or resulting rail failures attributable to either the exothermic welding or rail plug bonding procedures.

Maximum Operating Speed:	79 mph passenger 60 mph freight
Wheel Load:	33,000 pounds freight
Rail Defect Detection Frequency:	Four times annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 25

System Details:

- Operates and maintains a 222-route mile, overhead catenary, heavy rail commuter transit system with both passenger and freight service, and a 160-route mile, 600-volt

DC either third rail or overhead catenary, light rail transit system.
- Rail section is 100RB and 115RE on either ballasted or direct fixation track structure.

Currently, the 250-mcm and 500-mcm power cables are bonded to the web of the rail using exothermic welds. The 250-mcm signal cables are attached to the railhead with exothermic welds. Welding procedures are carried out in accordance with the manufacturer's guidelines and recommendations. The system does not have its own specific welding specifications or procedures.

Rail failure problems, including head and web separations, have occurred apparently due to fracture initiation in the weld area. In some cases, defects and broken rails have resulted from the exothermic welds being placed too close to existing bolt holes. No historical data are available to identify the number and type of rail failures; however, they generally occur at the rate of two or three failures annually.

The system is currently testing and evaluating the use of a rail web bolted connection as an alternative bonding procedure.

Maximum Operating Speed:	70 mph
Wheel Load:	12,500 pounds
Rail Defect Detection Frequency:	Once annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 26

System Details:

- Operates and maintains 74 route miles.
- Third rail 600-volt DC.
- Heavy rail transit system.
- Track structure includes 100 ARA-A and 115 RE continuous welded rail and jointed rail.
- Of the route miles, about 75 percent are direct fixation in tunnels, and 25 percent are open ballasted track with either concrete or timber crossties.

Rail bonding includes the use of 2/0 AWG signal wires attached to the railhead with exothermic welds. Both the 4/0 AWG ground bonds and the 500-mcm power bonds are attached to the rail web using exothermic welds. At transposition locations, four 500-mcm bonds are required using exothermic welds at 6-inch spacing on the rail web.

Rail defects attributed to exothermic welding of bonds are on the order of 5 to 10 annually as identified by nondestructive ultrasonic rail flaw testing. Rail failures include web cracks, very few of which lead to broken rails.

Maximum Operating Speed:	50 mph
Wheel Load:	15,000 pounds
Rail Defect Detection Frequency:	Every 18 months

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 27

System Details:

- Operates and maintains a 78-route-mile transit system, including 32 miles of overhead catenary light rail and 46 miles of third-rail-power heavy rail.
- Track structure varies with ballasted, direct fixation, open deck, or encased construction.
- Rail is control cooled, head hardened, 115 RE, and either CWR or jointed.
- Timber and concrete crossties.

Exothermic welds are used to attach the No. 6 AWG signal bonds to the railhead. The 250-mcm power cables are exothermically welded to either the railhead using C-bonds or to the rail web. Power bonding includes the application of either single or double cables. Rail bond testing is in compliance with AAR/AREMA-recommended practice.

Specific rail failure data are not readily available. Although not considered significant, web defect problem areas relating to exothermic bond welding include the positioning of bonds in close proximity to existing bolt holes, welded rail joints, or previously welded bonds.

Maximum Operating Speed:	50 mph
Wheel Load:	15,500 pounds
Rail Defect Detection Frequency:	Once annually

SUMMARY OF RESPONSES FROM TRANSIT SYSTEM 28

System Details:

- Owns 730 route miles.
- Both third rail and overhead catenary are used in the system.
- Track structures include ballasted and direct fixation, and both concrete and wood ties are used.
- Rail sections include 136RE and 140RE dated mid-1960 to present from various mills.
- The system has about 4,000 bonded rail joints in track.

Exothermic welds are used to attach 500-mcm cables to the railhead. Safety concerns include welding during damp or wet conditions. This can cause serious harm to people applying them, can lead to defective weld, and can cause bonds to be knocked off when they are not properly positioned. An alternative procedure for 500-mcm cable-to-rail bonding is web drilling and installing a collar and bolt in the rail.

Maximum Operating Speed:	60 mph
Wheel Load:	N/A
Rail Defect Detection Frequency:	Semi-annually

APPENDIX C

LABORATORY TEST RESULTS FOR RAIL MATERIALS AFTER MECHANICAL DRILLING

C1 CHEMICAL COMPOSITIONS

Chemical composition samples were taken from the adjacent rail materials of the tested drill holes. Four samples were taken from each drilling hole: two from the gage side and two from the field side of the rail. The two samples from each side were taken in different locations: one close to the hole radius (denoted R in sample ID) and the other away from the hole (denoted O in the sample ID). Table C-1 lists the chemical compositions for each sample. Current AREMA specifications are also included in the table for reference. The manganese residual element (nickel, chromium, molybdenum, and vanadium) limits may be varied by manufacturers in the specified ranges to meet mechanical property requirements.

C2 TENSILE PROPERTIES

One standard tensile specimen was taken from the adjacent rail material at the top of each drilled hole. The specimens were taken in such a manner that the specimen is tangent to, and its center is very close to, the hole circumference. The tensile properties are listed in Table C-2. AREMA requirements are also included in the table for reference.

C3 HARDNESS MEASUREMENTS

From each mechanically drilled hole, hardness was measured on both the gage side and the field side of the rail surfaces in 0.05-inch steps. There were hardness increases in the immediate vicinities of the holes, probably caused by work hardening as plastic deformation was evident in areas of increased hardness. Table C-3 lists the measured hardnesses in Vickers scale.

C4 MICROSTRUCTURES

Microstructures of rail materials close to each mechanically drilled hole were examined. It was evident that no phase transformation occurred during the drilling process. Local work hardening (plastic deformation) was apparent at the hole circumferences. Figures C-1 through C-8 present the microstructures (at 100× magnification) of rail material, in gage side or field side, close to each drilling hole.

C5 SUMMARY OF LABORATORY TEST RESULTS

The microstructures and hardness of the rail material around the drilling holes proved that no significant metallurgical transformation of the rail material occurred during the drilling process. Microstructures show limited plastic deformations at the edge of the holes, and the work-hardening effect is evident from the hardness variations, as shown in Table C-3.

The carbon contents of the hole-drilling test rails are at or slightly below the AREMA-required minimum of 0.74 percent, and the tensile strength of the rail material adjacent to Hole 3 is slightly below the AREMA requirement; otherwise, the tested rail materials meet AREMA requirements chemically and mechanically.

It can be concluded that there is no major metallurgical damage to the rail steel during the hole-drilling process.

TABLE C-1 Chemical compositions of rail steel close to mechanically drilled holes

Sample ID	Hole #1, 3/8-inch, used insert during in-track test				Current AREMA Specifications
	Field Side		Gage Side		
	1FR	1FO	1GR	1GO	
Carbon	0.73	0.70	0.70	0.72	0.74–0.84
Sulfur	0.007	0.008	0.006	0.007	<0.037
Phosphorus	0.016	0.017	0.015	0.015	<0.035
Silicon	0.29	0.28	0.28	0.28	0.10 – 0.60
Chromium	0.21	0.21	0.21	0.21	< 0.50
Nickel	0.01	0.01	0.01	0.01	<0.25
Manganese	1.15	1.14	1.16	1.16	0.60 – 1.25
Copper	0.1	0.01	0.01	0.01	N/A
Molybdenum	<0.01	<0.01	<0.01	<0.01	<0.10
Columbium	<0.01	<0.01	<0.01	<0.01	N/A
Titanium	<0.01	<0.01	<0.01	<0.01	N/A
Aluminum	<0.01	0.011	<0.01	<0.01	N/A
Vanadium	<0.01	<0.01	<0.01	<0.01	<0.05
Boron	<0.0005	<0.0005	<0.0005	<0.0005	N/A
Tungsten	<0.01	<0.01	<0.01	<0.01	N/A
Iron	Base	Base	Base	Base	Base
Sample ID	Hole #2, 3/8-inch, without insert during in-track test				Current AREMA Specifications
	Field Side		Gage Side		
	2FR	2FO	2GR	2GO	
Carbon	0.71	0.72	0.72	0.69	0.74–0.84
Sulfur	0.009	0.007	0.006	0.007	<0.037
Phosphorus	0.017	0.015	0.016	0.015	<0.035
Silicon	0.28	0.27	0.27	0.28	0.10 – 0.60
Chromium	0.22	0.21	0.21	0.21	< 0.50
Nickel	0.02	0.02	0.01	0.01	<0.25
Manganese	1.16	1.15	1.15	1.16	0.60 – 1.25
Copper	0.01	0.01	0.01	0.01	N/A
Molybdenum	<0.01	<0.01	<0.01	<0.01	<0.10
Columbium	<0.01	<0.01	<0.01	<0.01	N/A
Titanium	<0.01	<0.01	<0.01	<0.01	N/A
Aluminum	<0.01	<0.01	<0.01	<0.01	N/A
Vanadium	<0.01	<0.01	<0.01	<0.01	<0.05
Boron	<0.0005	<0.0005	<0.0005	<0.0005	N/A
Tungsten	<0.01	<0.01	<0.01	<0.01	N/A
Iron	Base	Base	Base	Base	Base

TABLE C-1 (Continued)

Sample ID	Hole #3, 3/8-inch, used insert during in-track test				Current AREMA Specifications
	Field Side		Gage Side		
	3FR	3FO	3GR	3GO	
Carbon	0.74	0.73	0.69	0.68	0.74–0.84
Sulfur	0.030	0.024	0.23	0.025	<0.037
Phosphorus	0.022	0.021	0.019	0.020	<0.035
Silicon	0.18	0.17	0.17	0.17	0.10 – 0.60
Chromium	0.03	0.03	0.024	0.024	<0.50
Nickel	0.06	0.06	0.06	0.06	<0.25
Manganese	0.92	0.90	0.90	0.90	0.60 – 1.25
Copper	0.07	0.07	0.07	0.07	N/A
Molybdenum	<0.01	<0.01	<0.01	<0.01	<0.10
Columbium	<0.01	<0.01	<0.01	<0.01	N/A
Titanium	<0.01	<0.01	<0.01	<0.01	N/A
Aluminum	0.017	0.018	0.011	0.011	N/A
Vanadium	<0.01	<0.01	<0.01	<0.01	<0.05
Boron	<0.0005	<0.0005	<0.0005	<0.0005	N/A
Tungsten	<0.01	<0.01	<0.01	<0.01	N/A
Iron	Base	Base	Base	Base	Base

Sample ID	Hole #4, 3/8-inch, without insert during in-track test				Current AREMA Specification
	Field Side		Gage Side		
	4FR	4FO	4GR	4GO	
Carbon	0.70	0.69	0.74	0.75	0.74–0.84
Sulfur	0.029	0.024	0.027	0.024	<0.037
Phosphorus	0.021	0.020	0.022	0.020	<0.035
Silicon	0.17	0.17	0.18	0.17	0.10 – 0.60
Chromium	0.03	0.02	0.03	0.02	<0.50
Nickel	0.06	0.05	0.06	0.06	<0.25
Manganese	0.90	0.90	0.91	0.90	0.60 – 1.25
Copper	0.07	0.07	0.07	0.07	N/A
Molybdenum	<0.01	<0.01	<0.01	<0.01	<0.10
Columbium	<0.01	<0.01	<0.01	<0.01	N/A
Titanium	<0.01	<0.01	<0.01	<0.01	N/A
Aluminum	0.012	0.010	0.010	0.010	N/A
Vanadium	<0.01	<0.01	<0.01	<0.01	<0.05
Boron	<0.0005	<0.0005	<0.0005	<0.0005	N/A
Tungsten	<0.01	<0.01	<0.01	<0.01	N/A
Iron	Base	Base	Base	Base	Base

TABLE C-2 Tensile properties of rail materials close to mechanically drilled holes

Specimen	#1	#2	#3	#4	AREMA spec. for standard rail
Yield Strength (psi)	91,800	91,000	79,100	81,800	> 70,000
Tensile Strength (psi)	151,900	153,100	137,700	140,100	> 140,000
Elongation (%)	14.0	13.0	11.5	10.0	> 9.0
Reduction Area (%)	32.3	27.3	16.9	15.8	N/A

TABLE C-3 Hardness of rail materials close to mechanically drilled holes

Distance from Hole (inch)	Hardness in Vickers							
	#1		#2		#3		#4	
	Gage	Field	Gage	Field	Gage	Field	Gage	Field
0.005	330.7	308.7	302.6	285.8	275.6	242.7	308.7	278.0
0.055	320.3	302.1	285.8	282.3	280.4	259.2	261.0	263.2
0.105	325.7	277.5	290.4	249.5	270.0	241.9	273.2	294.6
0.155	297.7	291.4	273.7	266.8	271.3	242.3	275.1	275.1
0.205	292.0	285.8	287.9	253.3	293.5	252.0	284.3	258.8
0.255	284.3	269.0	288.9	271.3	260.5	241.9	255.4	259.7

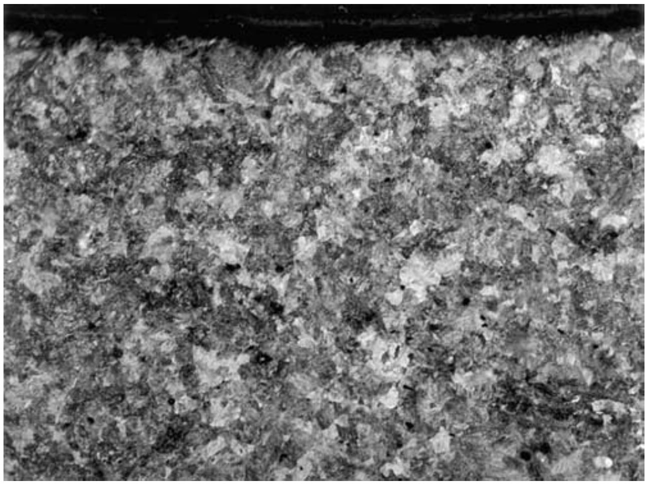


Figure C-1. Hole 1 at gage side.

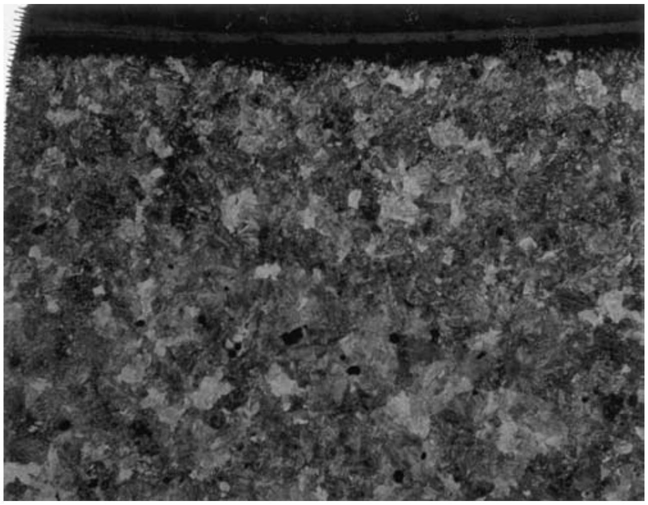


Figure C-2. Hole 1 at field side.

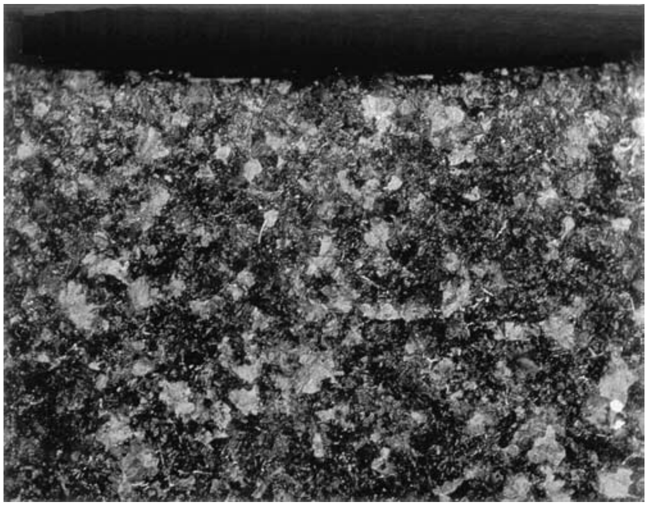


Figure C-3. Hole 2 at gage side.

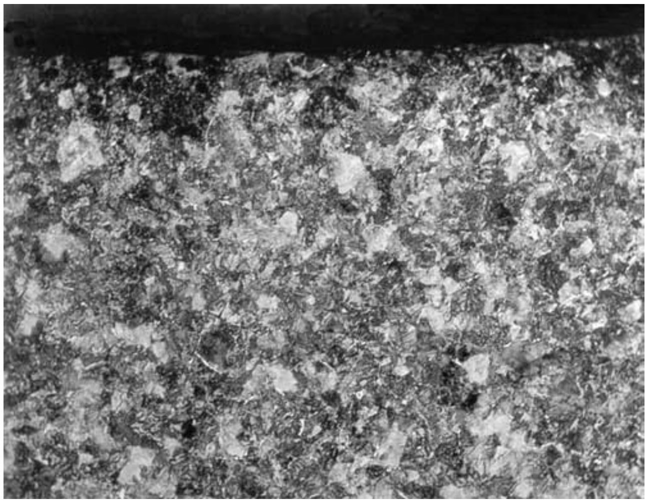


Figure C-4. Hole 2 at field side.

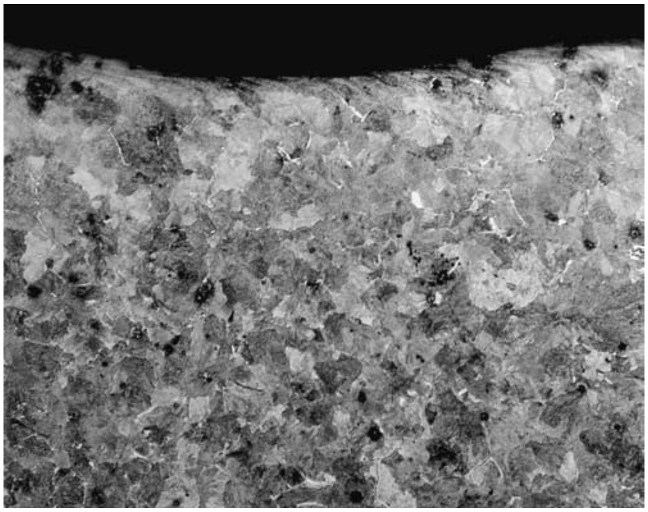


Figure C-5. Hole 3 at gage side.

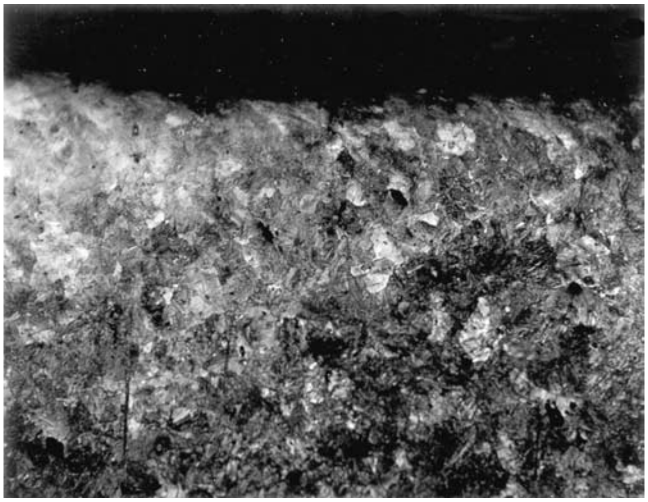


Figure C-7. Hole 4 at gage side.

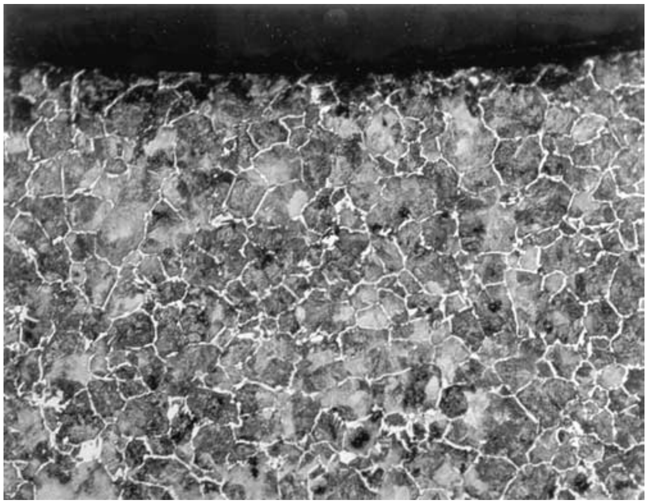


Figure C-6. Hole 3 at field side.

Figure C-8. Hole 4 at field side.

APPLICABILITY OF AREMA TRACK RECOMMENDED PRACTICES FOR TRANSIT AGENCIES

SUMMARY

The American Railway Engineering and Maintenance-of-Way Association's (AREMA's) *Manual for Railway Engineering* (hereafter referred to as the Manual) and *Portfolio of Trackwork Plans* (hereafter referred to as the Portfolio) are published as recommended practices intended to serve as guidelines for the development of individual railway policies and practices. Although AREMA is in the process of developing Manual chapters that are specific to transit and commuter rail systems, the current material is directed primarily toward the North American common-carrier freight railroad network. The purpose of this study is to review the applicability of current AREMA track recommendations to rail transit operations. This report identifies areas where AREMA recommendations may not apply to transit operations and identifies transit practices and components that are not addressed by AREMA.

AREMA track recommendations are based on track gage and the wheel profile and gage requirements found in Section G of the Association of American Railroads (AAR) Manual. These requirements are shown in Plan 793-52 of the *Portfolio of Trackwork Plans.* Commuter and heavy rail systems generally follow the 793-52 dimensions with some minor variations. Light rail systems, however, use a wide variety of wheel designs and gages, many of which are unique to a particular system.

Transit incompatibilities with AREMA recommendations, found to relate primarily to light rail wheel designs and wheel gages, are summarized as follows:

- Transit wheels with tread widths less than 4 inches (102 mm) are not compatible with AREMA design fixed-point frogs or low-angle crossings.
- The switch point designs in AREMA Plan 221-00 details 4000, 5100, and 6100 may allow wheel flange heights less than 1 inch (25 mm) to climb worn or chipped points.
- The AREMA flangeway width of 1⅞ inches (48 mm) is not compatible for wheel flanges less than $1\frac{5}{32}$ inches (29 mm) wide. Flangeway widths between 1½ and 1¾ inches (38 and 44 mm) are common in transit designs.
- AREMA tongue switch designs have flangeways that are too wide for wheels with flange widths less than $1\frac{5}{32}$ inches.
- The recommended wayside lubrication practices in Chapter 5 may not be compatible with transit operating practices.
- The AREMA tunnel clearance diagrams in Chapter 1 are intended for freight applications and may not be compatible with some transit vehicle outlines.

The following are track components, systems, and issues common to transit systems but not currently found in the AREMA Manual or Portfolio:

- Embedded track designs using girder and tee rail sections;
- European girder rail sections and procurement specifications;
- Guarded switch designs, including double guard designs, cover guard designs, and placement and turnout layout data;
- Design methodology for track gage widening and restraining rail flangeway widths for minimum radius curves based on flange dimensions, wheel gage, and axle spacing;
- Restraining rail design and recommended practices;
- Flange-bearing frog and crossing designs;
- European tongue switch designs;
- Switch point detail for flange heights less than 1 inch;
- Adjustable guardrail designs allowing flangeway widths less than 1⅞ inches;
- Stray current corrosion protection;
- Rail corrugation control; and
- Noise and vibration control.

1 INTRODUCTION

1.1 Background

The Manual includes theory, data, recommended specifications, plans, and economic analysis pertaining to the engineering, design, and construction of railway track and structures, excluding signals and communications. The Manual consists of four volumes:

- Track,
- Structures,
- Infrastructure and Passenger, and
- Systems Management.

The volumes are made up of chapters pertaining to specific elements of railway infrastructure engineering and management such as rail, ties, steel structures, and track measurement systems. The content of each chapter is developed and administered by a technical committee made up of AREMA members and associate members. Chapter revisions are published annually, and the AREMA Board of Directors provides committee oversight and final approval of revised manual material.

The Portfolio is a companion volume to the Manual. The Portfolio contains plans, data, and recommended specifications for special trackwork components and systems such as frogs, crossings, guardrails, switches, and turnouts.

The Manual and Portfolio are published as sets of ***recommended practices*** and, according to the Manual introduction, are intended to serve as guidelines for the development of individual railway policies and practices [1]. In some cases, such as the rail specifications and to some extent bridge design, the industry has found it beneficial to standardize using the AREMA recommended practices. In other areas, such as special trackwork, individual railway standards may differ significantly from the AREMA recommendations and may include designs and components not found in the AREMA recommended practices.

Although the AREMA recommended practices are intended to be as universal in their application as possible, the material is directed primarily toward the North American common-carrier freight railroad network. Rolling stock that operates in this environment is governed by the Association of American Railroads (AAR) *Manual of Standards and Recommended Practices*. The AREMA recommended practices are compatible with the AAR standards, the AAR wheel profile and wheel gage criteria in particular.

Rail transit systems, with the exception of some commuter rail operations, are not part of the general railroad network. Because some transit systems are removed from the network and must comply with requirements of the urban environments in which they operate, some transit systems have adopted wheel profile and wheel gaging specifications that are exclusive to their systems and substantially different from the AAR standards. These wheel specifications may be incompatible with some AREMA recommended practices, especially the special trackwork designs. In addition, many rail transit systems have track designs, features, and operating constraints that are not addressed in the AREMA Manual, including embedded track, restraining rail configurations, and noise and vibration requirements.

Recognizing the need to include transit-specific issues, AREMA added Chapters/Committee 12—"Rail Transit"—to the Manual in 1986 and Chapter/Committee 11—"Commuter and Intercity Rail Systems"—in 2002.

Both chapters will be in Volume 3 and are under development.

1.2 Purpose

The purpose of this study is to review existing AREMA track recommendations as to their applicability to rail transit operations. The review includes a survey of typical transit vehicle wheel profiles and wheel gaging specifications and a determination of where these differences affect the AREMA recommendations. The scope of the project will (1) identify areas where AREMA recommendations may not apply to transit operations and (2) identify practices and components that are common to transit systems but not addressed by AREMA.

1.3 Definition of Rail Transit Modes

The American Public Transportation Association (APTA) defines the following modes of rail transit operations in North America [2]:

Commuter rail (also known as regional rail) is an electric- or diesel-propelled suburban passenger train service consisting of local short-distance travel operations between a city center and adjacent suburbs. Service is operated on a regular basis from one or two central city stations to outlying areas. Using either locomotive-hauled or self-propelled passenger cars, commuter service is generally characterized by multi-trip tickets, specific station-to-station fares, and railroad employment practices. Commuter rail does not include intercity passenger rail service. Commuter rail operations often use existing or former freight railroad rights-of-way, and combined freight and commuter usage of these routes is possible. Commuter systems are, for the most part, at-grade ballasted track on dedicated rights-of-ways, and grade crossings are common on some routes. At least one commuter rail agency operates at speeds of 100 mph; however, the maximum speed on the majority of systems is 79 mph. There are 21 commuter rail agencies in the United States.

Heavy rail is a 600- to 750-volt direct-cable (DC), third-rail traction, urban railway with the capacity for heavy traffic volume and passenger density. It is characterized by rapid-acceleration passenger equipment operating in multi-unit trains and short train headways. Heavy rail systems operate on dedicated rights-of-way, often underground (i.e., subways), with very little or no shared freight or vehicular traffic. There are 14 heavy rail agencies in the United States.

Light rail (includes street cars and trams) is a 600- to 750-volt DC, overhead traction (via trolley or pantograph), urban railway using lightweight passenger rail cars operating singly or in short (usually two-car) trains. Light rail track designs tend to be more diverse than commuter or heavy rail. They may use dedicated rights-of-way at grade, on elevated structures, or underground. Light rail systems frequently share streets with vehicular and pedestrian traffic, and train speeds are generally slower than commuter or heavy rail operations. Several cities have implemented new light rail operations in the past 20 years, and 26 agencies are currently in operation nationwide.

Automated guideway transit (also known as a "people mover") is an electric railway (single or multi-car trains) of guided transit vehicles operating without an onboard crew. Service may be on a fixed schedule or in response to a passenger-activated call button. Automated guideways currently exist in Detroit, Michigan; Jacksonville, Florida; Miami, Florida; and Morgantown, West Virginia. Automated guideways in non-transit settings such as airports are also common. Table 1 provides a breakdown of the route mileage by transit mode and track construction type.

2 TRANSIT WHEEL PROFILE, WHEEL GAGE, AND TRACK GAGE

2.1 Commuter and Heavy Rail Systems

Commuter and heavy rail systems generally follow the AREMA wheel and track gage design shown in Plan 793-52 in the Portfolio (Figure 1) [4]. The data in Plan 793-52 is based on the wheel profile and wheel gage criteria found in Section G of the AAR Manual. Plan 793-52 uses the recommended track gage of 56½ inches (1,435 mm) and establishes the AREMA recommended flangeway width of 1⅞ inches (48 mm).

The AAR-1B narrow flange wheel profile shown in Figure 2 is commonly used in commuter systems. The AAR-1B wheel tread and flange angle profiles are more varied in heavy rail systems (at least one system uses a cylindrical tread and one system use a flange angle of 65 degrees), although the 1 5/32-inch (29-mm) flange width is common.

The wheel gage of 55 11/16 inches (1,415 mm) for narrow flange wheels and 55 27/32 inches (1,418 mm) for wide flange wheels found in Plan 793-52 allows flange-to-rail clearances of 13/32 inches (10 mm) and 21/64 inches (8 mm) for the centered narrow and wide flange wheels, respectively. The back of wheel-to-guardrail clearances are 5/16 inches (8 mm) and 11/64 inches (4 mm) for centered narrow and wide flange wheels, respectively.

The tread width (i.e., distance from the wheel gage point to the outside of the rim) is 4 11/32 inches (110 mm). The AAR also recognizes a cylindrical tread profile that is identical to the narrow flange profile with no tread taper. At least one heavy rail system uses the cylindrical profile as noted above.

Some heavy rail systems specify a modified track gage of 56¼ inches (1,429 mm) on tangent track, and most systems widen the track gage on curves with radii less than 350 feet (107 m).

2.2 Light Rail

Light rail systems use a wide variety of wheel designs, many of which are unique to a particular system. Light rail systems also use a variety of wheel gages. These non-AAR wheel designs reflect the objective of many light rail systems to minimize vehicle weight and address design issues imposed by the use of girder rail in embedded track.

Light rail wheel diameters vary from 26 inches (660 mm) to 28⅜ inches (721 mm). A listing of light rail track and wheel gage data found in *TCRP Report 57: Track Design Handbook for Light Rail Transit* indicates that 59½-inch (1,435-mm) track gage is common to most systems, although wide gages of 62¼ inches (1,581 mm) and 62½ inches (1,588 mm) are noted [6]. Wheel gage specifications for systems using standard track gage vary from 55 47/100 inches (1,409 mm) to 56¼ inches (1,429 mm), and the wheel-flange-to-rail clearances vary from ½ inch (13 mm) to ⅛ inch (3 mm), respectively.

Light rail wheel tread widths also vary considerably, ranging from the AAR standard 4 11/32 inches (110 mm) to 2½ inches (64 mm). Tread widths are critical to the use of

TABLE 1 Breakdown of rail transit mileage by mode and track type [3]

Mode	Elevated	Surface	Underground	Total
Guideway	8.3	9.4	0.0	17.7
Commuter Rail	64.3	7,249.1	39.5	7,352.9
Heavy Rail	481.4	917.4	780.3	2,179.1
Light Rail	49.0	981.5	63.1	1,093.6
TOTAL	603.0	9,157.4	882.9	10,643.3

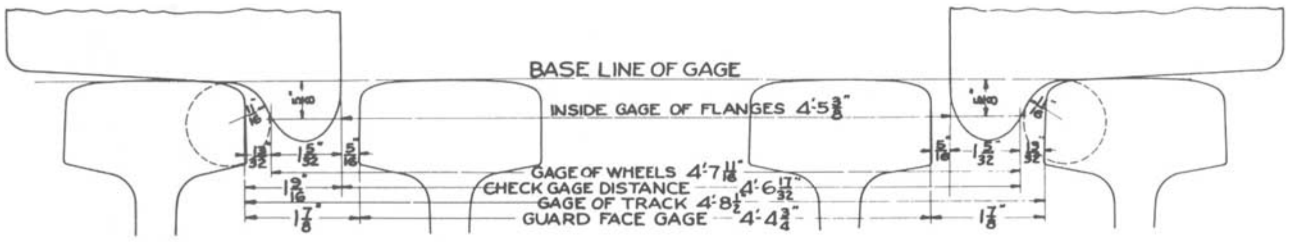


Figure 1. AREMA Plan 793-52 recommended wheel and track gaging for narrow flange wheels.

fixed-point frogs and low-angle crossings. Widths less than approximately 4 inches (102 mm) are not compatible with AREMA designs, as will be discussed in the next section. Light rail wheel tread tapers vary from 1:20 to cylindrical with tapers of 1:40, 1:32, and 1:30 included. Light rail flange widths and heights are also variable, with some widths and/or heights being less than 1 inch (25 mm).

3 REVIEW OF AREMA TRACK RECOMMENDATIONS IN RELATION TO RAIL TRANSIT

The following subsections will discuss the applicability of the AREMA recommended practices found in the Manual chapters and in the Portfolio dealing specifically with track. Relevant sections of non–track-specific chapters will also be discussed.

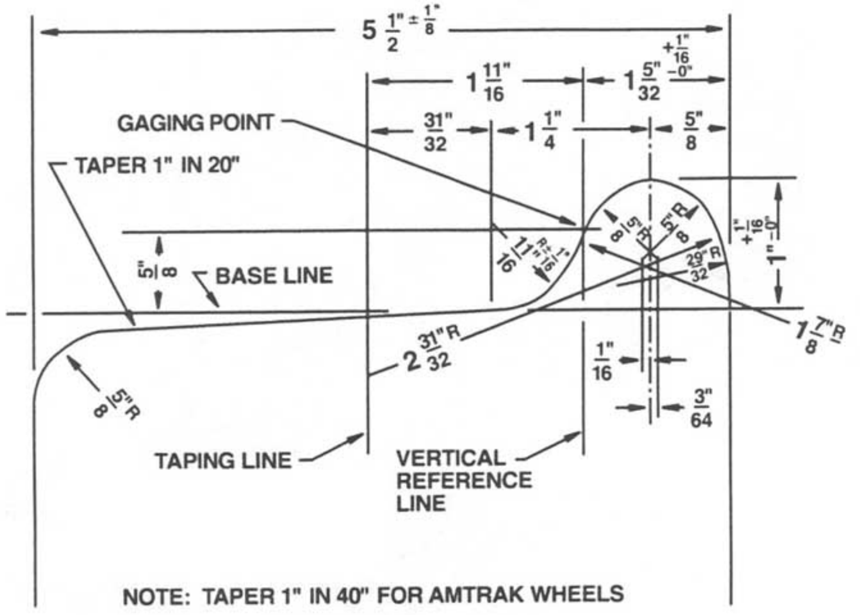
3.1 Chapter 1—Roadway and Ballast

The AREMA recommendations for roadway, ballast, natural waterways, culverts, pipelines, fences, roadway signs, vegetation control, and geosynthetics (Chapter 1 Parts 1–7, 9, and 10) are applicable to at-grade ballasted track transit construction, although some of these recommendations may be superseded by local regulations and ordinances.

The clearances shown in Part 8, “Tunnels,” may not be applicable to heavy and light rail systems.

3.2 Chapter 4—Rail

The AREMA 115RE rail section (Figure 3) is the recommended tee-rail section for most heavy and light rail systems. Obsolete AREMA and non-AREMA rail sections may still be used where overhead clearance restrictions or other struc-



NOTE: TAPER 1" IN 40" FOR AMTRAK WHEELS

Figure 2. AAR-1B narrow flange wheel profile [5].

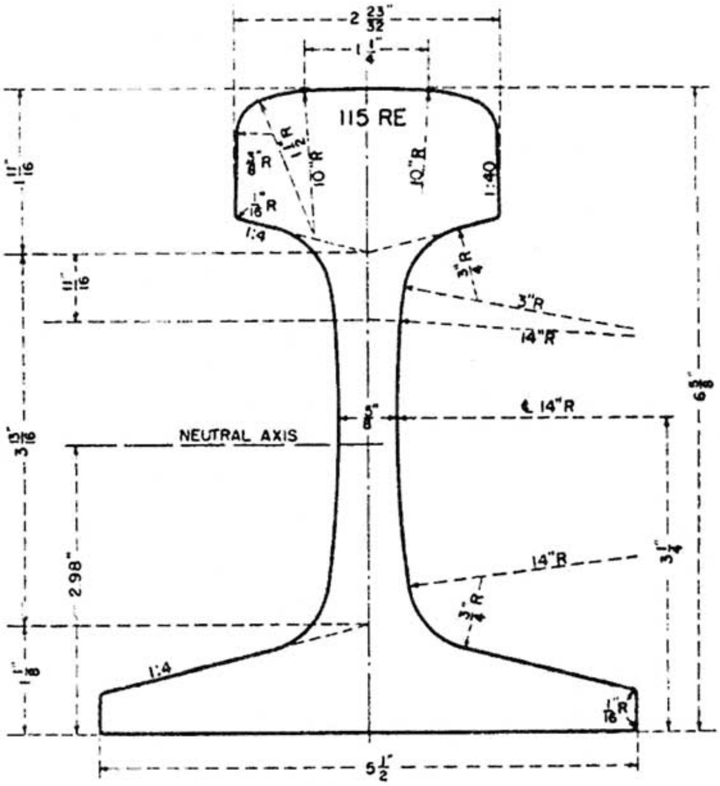


Figure 3. AREMA 115lb rail profile [7].

tural or access considerations make it more cost-effective to leave the 115RE rail unchanged. Commuter rail systems may use one or more of the heavier AREMA sections, such as 132RE or 136RE. All the transit wheel designs are compatible with current AREMA rail profile designs that have head radii greater than 8 inches. These include 115RE, 119RE, 132RE, 133RE, and 136RE.

The rail manufacturing guidelines; rail joint bar, bolt, and washer designs and guidelines; rail welding guidelines; and insulated rail joint guidelines found in Chapter 4 are all suitable for transit applications.

Plan 1002-84 of the Portfolio shows four girder rail sections: 128 RE 7 A, 149 RE 7 A, 159 RE 9 A, and 174 RE 9 A as information only. Although in use by some light rail systems, these girder rail sections are considered to be obsolete, and it is doubtful that new rail can be procured. New girder rail purchases are, therefore, likely to be of a European section.

3.3 Chapter 5—Track

Chapter 5 of the Manual contains a number of subsections with recommended practices relating to track, including the following subsections: tie plates, track spikes, rail anchors, curves, track maintenance, track construction, specifications and plans for track tools, highway-railway crossings, and design qualification specifications for elastic fasteners on timber cross ties. The following summarizes the applicability of these subsections for transit use.

3.3.1 Tie Plates, Track Spikes, and Rail Anchors

AREMA design tie plate recommendations are compatible with any transit track design using timber ties or plastic/composite ties with track spikes and rail anchors as the rail fastening system. The recommended tie plate rail cant is 1:40; however, different cant values may be specified. The rail anchor recommendations, including the slip and fracture test recommendations, are all appropriate for transit use. Currently, no AREMA recommended design has been developed for tie plates designed for elastic rail fasteners.

3.3.2 Curves

AREMA recommends a minimum spiral length that equates to a rate of change of the unbalanced lateral acceleration acting on a passenger not exceeding 0.03 *g* per second (Equation 1) and a maximum superelevation rate of change of $\frac{1}{744}$, which is based on the racking and torsional force response of a 85-foot-long car (Equation 2). These criteria are conservative for commuter and heavy rail operations in which an 85-foot-long car may be used and are extremely conservative for vehicles that are significantly shorter. AREMA also provides a less conservative method based on the rate of change of the unbalanced lateral acceleration acting on a passenger not exceeding 0.04 *g* per second (Equation 3).

$$L_s = 1.63E_uV \qquad (1)$$

where
L_s = length of spiral (feet),
E_u = unbalance superelevation (inches), and
V = maximum train speed (mph).

$$L_s = 62E_a \qquad (2)$$

where E_a = actual superelevation.

$$L_s = 1.22E_uV \qquad (3)$$

TCRP Report 57 recommends a spiral length as the greater value calculated from three formulas [8]:

$$L_s = 0.82E_uV \qquad (4)$$

$$L_s = 31E_a \qquad (5)$$

$$L_s = 1.10E_aV \qquad (6)$$

Table 2 shows a comparison of spiral lengths calculated with the above methods for a curve in which $E_a = 4$ inches (102 mm), $E_u = 3$ inches (76 mm), and $V = 45$ mph (77 km/h). The most conservative of the calculations (Equation 6) is in reasonable agreement with the AREMA optimum ride quality value of Equation 1. This comparison indicates that unless constrained by existing alignments or physical obstructions in new construction, the AREMA spiral length calculation based on optimum passenger comfort is not overly conservative for transit track designs.

Following the determination of spiral length, the AREMA recommended method of spiral design and layout are acceptable for transit application.

The following subsections of the AREMA Manual Chapter 3 are all acceptable for transit applications:

- Subsection 3.2, "String Lining of Curves by the Chord Method";
- Subsection 3.3, "Elevation and Speeds Through Curves";
- Subsection 3.4, "Speeds of Trains Through Level Turnouts";
- Subsection 3.5, "Minimum Tangent Lengths Required Between Reverse Curves for Yard Operations";
- Subsection 3.6, "Vertical Curves";
- Subsection 3.7, "Compensated Gradients"; and
- Subsection 3.8, "Permanent Monuments."

3.3.3 Track Maintenance, Track Construction, and Specifications and Plans for Track Tools

The recommended practices in these three sections of Chapter 5 are general in nature and should apply to transit use on ballasted track with the following possible exceptions:

- The joint stagger recommendation in Section 4.1(u) may not be considered necessary.
- The recommended use of frogs in Section 4.2 will not apply to some light rail systems due to wheel dimensions.
- The wayside lubrication of rail on curves in Section 5.9 may not be compatible with the operating practices of light and heavy rail systems.

3.3.4 Highway-Railway Crossings

Highway or grade crossings pertain primarily to commuter and light rail systems. The AREMA recommendations apply to commuter rail systems. With the exception of recommended flangeway widths, which may be wider than light rail flangeway designs, the AREMA recommendations for highway or grade crossings apply to light rail systems.

3.3.5 Design Qualification Specifications for Elastic Rail Fasteners on Timber Cross Ties

The AREMA qualification tests for elastic rail fasteners on timber ties are applicable for transit use with the following exceptions:

- The lateral and vertical loads recommended in Subsection 9.3.6, "Repeated Load Test," should be adjusted to reflect the same *L*/*V* ratios with actual vertical wheel loads.

TABLE 2 Comparison of AREMA and TCRP light rail design spiral lengths (feet)

Method	L_s
Equation 1 (AREMA 0.03 g/sec rate of change of the unbalanced lateral acceleration)	220
Equation 2 (AREMA 1/744 maximum rate of superelevation change)	248
Equation 3 (AREMA 0.04 g/sec rate of change of the unbalanced lateral acceleration)	165
Equation 4 (TCRP recommended light rail design)	110
Equation 5 (TCRP recommended light rail design for 1/372 maximum rate of superelevation change)	124
Equation 6 (TCRP recommended light rail design)	198

- The tie spacing for the repeated load test should reflect the actual tie spacing rather than the 19.5 inches (495.3 mm) recommended.

3.4 Chapter 30—Ties

The AREMA recommended specifications and practices for ties are acceptable for transit ballasted track applications.

3.5 Portfolio of Trackwork Plans

3.5.1 Switches

3.5.1.1 Split Switches. The AREMA designs for tee-rail straight and curved split switches found in the Portfolio are compatible with transit wheel designs with flange heights of at least 1 inch (25 mm) at a wheel gage of 55$\frac{11}{16}$ inches (1,414 mm). For light rail wheel designs with flange heights less than 1 inch (25 mm) and wheel gages wider than 55$\frac{11}{16}$ inches (1,414 mm), the depth of the switch point tip below the top of the stock rail of ⅝ inch (16 mm) for AREMA point details 4000 and 6100, and $\frac{11}{16}$ inches (17 mm) for point detail 5100, increases the risk of wheels climbing chipped or worn points.

3.5.1.2 Tongue Switches. The Portfolio includes plans for four tongue switch designs (Plans 982-60, 987-60, 988-60, and 989-60). In addition, Plan 980-60 gives turnout and crossover data for tongue switch construction in pavement. The AREMA designs include straight double tongue switches and a 200-foot radius tongue switch and mate. The AREMA double tongue designs are for locomotives with driving trucks having two, three, or more than three flanged wheels. The 200-foot radius is for locomotives with two-axle driving trucks.

Because the AREMA tongue switches are designed for AAR wheel profiles and wheel gages, the flangeway widths may be too wide for wheel designs with flange widths less than 25 mm.

3.5.2 Turnouts

AREMA turnout geometries shown in Plans 910-41 and 920-51, the switch tie design shown in Plan 912-58, and the location of joints found in Plan 921-52 apply to transit vehicles.

3.5.3 Frogs, Crossings, and Guard Rails

All AREMA fixed-point frog designs, including rail-bound manganese and self-guarded solid manganese, are compatible with transit wheels having tread widths greater than 4 inches (102 mm). Wheels with tread widths less than 4 inches are not wide enough to make the transition from the frog throat to the point and are incompatible with the AREMA fixed-point design. Although AREMA spring-rail frogs provide an acceptable option, light rail systems with narrow wheel treads typically use flange-bearing frogs. AREMA does not currently have a flange-bearing frog design. The same narrow tread issue exists for crossing frogs with angles less than about 25 degrees.

AREMA frog, crossing, and guardrail designs all use a flangeway width of 1⅞ inches (48 mm). The AREMA flangeway width is too wide for transit wheels with flange widths less than the AAR narrow flange width of 1$\frac{5}{32}$ inches (29 mm) and a wheel gage greater than 55$\frac{11}{16}$ inches (1,415 mm). To maintain adequate clearance at frog points with light rail wheel designs, the flangeway width should be reduced to 1¾ inches (44 mm) or 1½ inches (38 mm) depending on the flange width and wheel gage. The AREMA recommendations for guardrail placement shown in Plan 502-00 are acceptable for transit use.

3.6 Chapter 8, Part 27–Concrete Slab Track

The AREMA slab and direct fixation track design and construction recommendations in Chapter 8, Part 27, are compatible with transit vehicle designs.

4 SUMMARY OF RESULTS AND DISCUSSION

Table 3 summarizes AREMA track recommendations that potentially are not compatible with rail transit modes and transit-specific practices that are not found in the AREMA Manual and Portfolio. (Note: the automated guideway mode is not included.)

4.1 Discussion of AREMA Recommended Practices that Are Potentially Non-Compliant with Transit Operations

- Transit wheels with tread widths less than 4 inches (102 mm) are not compatible with AREMA design fixed-point frogs or low-angle crossings. Systems using these wheel designs must use spring rail, movable point, or flange-bearing frogs/crossings. Flange-bearing frogs are the preferred solution and are used by several light rail systems.
- The switch point designs in AREMA Plan 221-00 details 4000, 5100, and 6100 may allow wheel flange heights less than 1 inch (25 mm) with wheel gages wider than 55$\frac{11}{16}$ inches (1,415 mm) to climb worn or chipped points. A switch point detail with the point tip located no less than ¼ inch (6 mm) from the top of the stock rail would be more compatible for these wheel designs.
- The AREMA flangeway width of 1⅞ inches (48 mm) is not compatible with wheel flanges less than 1$\frac{5}{32}$ inches (29 mm) wide combined with wheel gages greater than 55$\frac{11}{16}$ inches at standard track gage. Flangeway widths between 1½ and 1¾ inches (38 and 44 mm) are common in transit designs.

TABLE 3 Results summary

AREMA	Commuter Rail	Heavy Rail	Light Rail
Chapter 1. Roadway and Ballast	**Potentially Not Compatible** • None	**Potentially Not Compatible** • Tunnel clearances shown in Part 8 – Tunnels	**Potentially Not Compatible** • Tunnel clearances shown in Part 8 – Tunnels
	Transit Practices Not Found in AREMA • None	**Transit Practices Not Found in AREMA** • None	**Transit Practices Not Found in AREMA** • Embedded track designs
Chapter 4. Rail	**Potentially Not Compatible** • None	**Potentially Not Compatible** • 8-inch head radius on 141RE rail section	**Potentially Not Compatible** • 8-inch head radius on 141RE rail section
	Transit Practices Not Found in AREMA • None	**Transit Practices Not Found in AREMA** • None	**Transit Practices Not Found in AREMA** • Non-obsolete girder rail sections and procurement specifications
Chapter 5. Track	**Potentially Not Compatible** • Wayside rail lubrication practices (5.9)	**Potentially Not Compatible** • Wayside rail lubrication practices (5.9) • Spiral length calculation (3.1) may be overly conservative • Load and tie spacing criteria in Design Qualification Specs for elastic fasteners (Part 9)	**Potentially Not Compatible** • Wayside rail lubrication practices (5.9) • Spiral length calculation (3.1) may be overly conservative • Load and tie spacing criteria in Design Qualification Specs for elastic fasteners (Part 9)
	Transit Practices Not Found in AREMA • Elastic fastener tie plates • Noise and vibration control	**Transit Practices Not Found in AREMA** • Elastic fastener tie plates • Restraining rail design • Gage-widening methodology • Noise and vibration control • Stray current corrosion control	**Transit Practices Not Found in AREMA** • Elastic fastener tie plates • Restraining rail design • Gage-widening methodology • Noise and vibration control • Stray current corrosion control
Chapter 8. Concrete Structures and Foundations, Part 27 – Concrete Slab Track	**Potentially Not Compatible** • None	**Potentially Not Compatible** • None	**Potentially Not Compatible** • None
	Transit Practices Not Found in AREMA • None	**Transit Practices Not Found in AREMA** • None	**Transit Practices Not Found in AREMA** • None
Chapter 30. Ties	**Potentially Not Compatible** • None	**Potentially Not Compatible** • None	**Potentially Not Compatible** • None
	Transit Practices Not Found in AREMA • None	**Transit Practices Not Found in AREMA** • None	**Transit Practices Not Found in AREMA** • None
Portfolio of Trackwork Plans	**Potentially Not Compatible** • None	**Potentially Not Compatible** • None	**Potentially Not Compatible** • Fixed-point frog designs • 1 ⅞-inch flangeway • Switch point designs (Plan 221-00 details 4000, 5100, and 6100) • Tongue switch designs
	Transit Practices Not Found in AREMA • None	**Transit Practices Not Found in AREMA** • Guarded switches • Turnout designs with restraining rails	**Transit Practices Not Found in AREMA** • Guarded switches • Turnout designs with restraining rails • Flange-bearing frogs • European tongue switch designs

- AREMA tongue switch designs have flangeways that are too wide for wheels with flange widths less than $1\frac{5}{32}$ inches.
- The recommended wayside lubrication practices in Chapter 5 may not be compatible with transit operating practices.
- The AREMA tunnel clearance diagrams in Chapter 1 are intended for freight applications and may not be compatible with some transit vehicle outlines.

4.2 Summary of Transit Practices Not Addressed by AREMA

The following are track components, systems, and issues common to transit systems but not currently found in the AREMA Manual or Portfolio:

- Embedded track designs using girder and tee-rail sections.
- European girder rail sections and procurement specifications.
- Guarded switch designs, including double guard designs, cover guard designs, and placement and turnout layout data. Figure 4 is an example of a 13-foot (3.96-m) guarded switch with cover guard located at the Federal Railroad Administration's Transportation Technology Center showing typical non-AREMA elements.
- Design methodology for track gage-widening and restraining rail flangeway widths for minimum radius curves based on flange dimensions, wheel gage, and axle spacing.
- Restraining rail design and recommended practices.
- Flange-bearing frog and crossing designs.
- European tongue switch designs.
- Switch point detail for flange heights less than 1 inch.
- Adjustable guardrail designs allowing flangeway widths less than 1⅞ inches.
- Stray current corrosion protection.
- Rail corrugation control.
- Noise and vibration control.

5 REFERENCES

1. AREMA, *Manual for Railway Engineering,* Volume 1 Introduction, 2003.
2. APTA, http://www.apta.com/research/stats/rail/definitions.cfm.

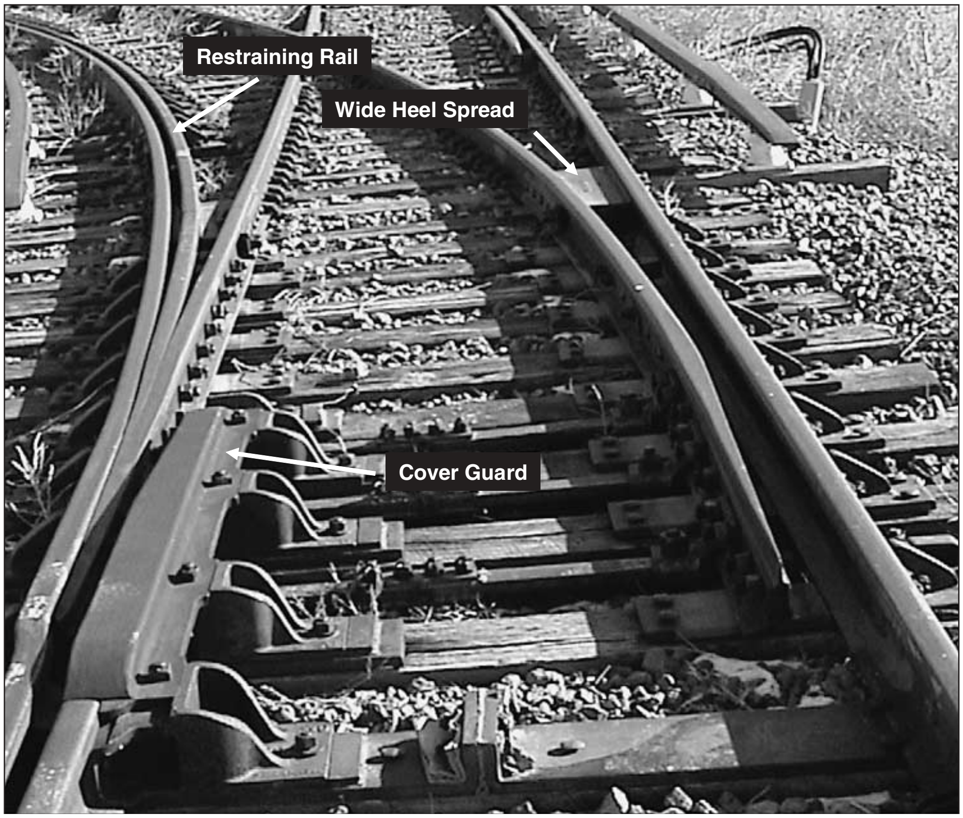


Figure 4. Typical guarded switch with cover guard.

3. Federal Transit Administration, 2002 National Transit Database, Table 23—Transit Way Mileage Rail Modes.
4. AREMA, *Portfolio of Trackwork Plans,* Plan 793-52, 2003.
5. AAR, *Manual of Standards and Recommended Practices*, Section G—Wheel and Axle Manual, Figure 4.31, Issue 2000.
6. *TCRP Report 57: Track Design Handbook for Light Rail Transit*, Chapter 2, Transportation Research Board, National Research Council, Washington, D.C., 2000.
7. AREMA, *Manual for Railway Engineering,* Volume 1, Chapter 4, Section 1.1, 2003.
8. *TCRP Report 57: Track Design Handbook for Light Rail Transit*, Chapter 3, Transportation Research Board, National Research Council, Washington, D.C., 2000.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
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	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
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
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation