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## Stray Current Control of Direct Current-Powered Rail Transit Systems: A Guidebook (2020)

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### CONTRIBUTORS

Emer C. Flounders, Jr., CORRPRO COMPANIES, INC, Advanced Engineering Services Group and HNTB Corporation Saud A. Memon; Transit Cooperative Research Program; Transportation Research Board; National Academies of Sciences, Engineering, and Medicine

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TRANSIT COOPERATIVE RESEARCH PROGRAM

TCRP RESEARCH REPORT 212

**Stray Current Control  
of Direct Current-Powered  
Rail Transit Systems:  
A Guidebook**

**Emer C. Flounders, Jr.**  
CORRPRO COMPANIES, INC.  
ADVANCED ENGINEERING SERVICES GROUP  
Malvern, PA

**Saud A. Memon**  
HNTB CORPORATION  
Houston, TX

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*The National Academies of*  
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TRANSPORTATION RESEARCH BOARD

2020

## 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, adapt appropriate new technologies from other industries, and 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 successful National Cooperative Highway Research Program (NCHRP), undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes various 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 of Sciences, Engineering, and Medicine, 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) Commission.

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

## TCRP RESEARCH REPORT 212

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## **CRP STAFF FOR TCRP RESEARCH REPORT 212**

**Christopher J. Hedges**, *Director, Cooperative Research Programs*  
**Lori L. Sundstrom**, *Deputy Director, Cooperative Research Programs*  
**Gwen Chisholm Smith**, *Manager, Transit Cooperative Research Program*  
**Stephan A. Parker**, *Senior Program Officer*  
**Stephanie L. Campbell**, *Senior Program Assistant*  
**Eileen P. Delaney**, *Director of Publications*  
**Natalie Barnes**, *Associate Director of Publications*  
**Linda A. Dziobek**, *Senior Editor*

## **TCRP PROJECT D-16 PANEL** **Field of Engineering of Fixed Facilities**

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**Melvin Clark**, *LTK Engineering Services, Flower Mound, TX*  
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**Robert S. Vail**, *AECOM, Atlanta, GA*  
**Roy Wei Shun Chen**, *FTA Liaison*  
**Louis F. Sanders**, *APTA Liaison*  
**Scott Babcock**, *TRB Liaison*

  
FOREWORD

By **Stephan A. Parker**

Staff Officer

Transportation Research Board

*TCRP Research Report 212: Stray Current Control of Direct Current-Powered Rail Transit Systems: A Guidebook* documents best practices for those seeking guidance on design, maintenance, and testing of stray current control (SCC) for rail transit systems. *TCRP Research Report 212* is based on a study of both national and international transit agencies and is formatted as a reference guide. It not only includes information and resources needed to implement and evaluate SCC and mitigation measures but also lists testing and maintenance strategies for transit operators. Stray current is the part of the current caused by a direct current (DC)-traction system that follows paths other than the return circuit. Stray current leakage and the corrosion caused by these currents is more of an issue in low resistivity soils and embedded tracks, which typically run through major traffic areas, city centers, and threads between utility lines that require the rail to be continuously isolated to provide superior track-to-earth resistance.

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Direct current (DC)-powered transit systems have been faced with major repairs and modifications to signal and traction power systems because of ineffective negative return rail isolation. An indication of the magnitude of the financial costs is cited in a comprehensive research report published by the IEEE in the 1990s, which estimated that a major portion of the \$500 million per year from stray current corrosion losses was borne by DC-powered transit properties and the surrounding infrastructure assets. This figure does not take into account the costs associated with signal problems and repairs. The cost to DC-powered transit systems has been increasing steadily due to stray current issues.

The overall objective of TCRP Project D-16 was to develop a guidebook on design and sustainability of SCC and control of railcar-to-earth and rail-to-earth voltages for DC-powered rail transit systems. This includes (a) a primer that explains all significant issues in readily understandable terms for nontechnical people, (b) guidelines addressed to design and maintenance practitioners, (c) historical performance data (based on agency interviews) of third rail and overhead contact, and (d) recommendations for further research.

Led by co-principal investigators Emer Flounders and Saud Memon, the research team began by assembling and undertaking a thorough review of data and current operating practices from

- National and international resources;
- Technical journals;
- Conference papers;
- Transit agency design criteria documents;

- International standards;
- Transit agency test results and maintenance documents; and
- Related reports by transit agencies, consultants, and organizations.

A mix of 30 transit agencies (21 national and 9 international) that responded to the questionnaires or participated in interviews augmented the literature review effort. This was supplemented with in-person interviews of eight stray current corrosion consultants and face-to-face interviews and testing of selected transit agencies. This guidebook also includes four anonymized case study SCC sites. They are as follows: (a) an agency with relatively newly constructed tracks; (b) an agency with older tracks; (c) an agency with tracks under construction (both light rail transit and heavy rail transit); and (d) an international transit agency with overhead contact systems.

Key decision matrices associated with implementing, maintaining, and testing of SCC and safety control of rail-to-earth potentials were developed using the information collected from the literature review, questionnaires, data gathered during the transit agencies' and corrosion consultants' interview process, and SCC testing observations. Using these findings, proactive sequential steps are presented in the guidebook for stray current isolation and quality control. These steps include measures that need to be taken at the inception of design, at preconstruction, at construction, and at postconstruction, leading into the maintenance and testing program phase during the revenue service of the transit system. These recommendations, if followed, will help to ensure that uniform stray current isolation and quality control are achieved for a DC-powered transit system.

This guidebook and a PowerPoint presentation describing the project are available on the TRB website at [www.trb.org](http://www.trb.org) by searching on "*TCRP Research Report 212*".

  
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S U M M A R Y

# Stray Current Control of Direct Current-Powered Rail Transit Systems: A Guidebook

This guidebook documents best practices for those seeking guidance on design, maintenance, and testing of stray current control for direct current (DC)-powered rail transit systems. The guidebook includes the study of both national and international transit agencies and is formatted as a reference guide for finding the information and resources needed to implement and evaluate not only stray current control (SCC) and mitigation measures but also the testing and maintenance strategies for transit operators.

The overall objective of the Transit Cooperative Research Program's Project D-16 was to develop a guidebook on design and sustainability of SCC and control of railcar-to-earth and rail-to-earth voltages for DC-powered rail transit systems. The guidebook includes (a) a primer that explains all significant issues in readily understandable terms for nontechnical people, (b) guidelines addressed to design and maintenance practitioners, (c) historical performance data (based on agency interviews) of third rail and overhead contact, and (d) recommendations for further research.

Besides achieving the preceding objectives, the guidebook also addresses the following fundamental questions:

- What is stray current?
- How do I know I have it?
- What do I do to mitigate it?
- What levels of stray current are acceptable?
- What levels of rail-to-earth potential are acceptable?
- What levels of track-to-earth and rail-to-rail resistance are required?
- What maintenance testing is required and how is the testing to be conducted?

This guidebook is the recent effort undertaken by the Transit Cooperative Research Program (TCRP) to provide a user-friendly framework of consolidated guidelines and recommendations that will help in mitigating or potentially eliminating stray current leakage from DC-operated rail tracks by using the data collected from transit agency and corrosion consultant interviews, stray current corrosion survey questionnaires, and field testing. The guidebook presents a progression from initial considerations of establishing a baseline survey for investigating the potential stray current risk to recommending mitigation and collection methods during construction and operation. The guidebook also recommends potential testing and maintenance strategies to control or minimize the leakage of stray current.

There are five chapters plus five appendices:

Chapter 1 defines the methodology of the research done in the preparation of the guidebook and explains the various terms used in the subsequent sections of this guidebook.

## 2 Stray Current Control of Direct Current-Powered Rail Transit Systems: A Guidebook

Chapter 2, which is the literature review section, gives a brief outline of the process of corrosion and the different traction power alternatives available to the transit agencies. This chapter documents and explains previous work on the control and mitigation of stray current corrosion, including the review and study of national and international design criteria and standards. The study and investigation encompass the review of theoretical and practical approaches, as well as experimental approaches, to address the stray current leakage and stray current corrosion issue in DC-powered transit systems. Some of the literature studied includes calculations for limiting stray current leakage by using various mitigation methods; this aids in justifying the potential enforcement of the recommended limiting values and testing requirements.

Chapter 3 discusses the process of SCC or collection system at different real-world DC-powered rail transit agencies, including their design criteria, operation modes, physical environment, track construction type, and testing methods. The data for this discussion were assembled by communicating with the respective transit agency representatives by using custom-made questionnaires (questionnaires along with the responses are provided in the appendices). In-person interviews of stray current corrosion consultants and conducting face-to-face interviews and testing of selected transit agencies supplemented the data.

Additionally, information on a select few transit systems was acquired through study of the transit agency performance, testing procedures, maintenance standards, and actual stray current testing. The chapter elaborates on the various stray current testing procedures and their results for existing transit systems, including a startup transit system in the United States and an international transit operator.

Chapter 4 provides a synopsis of the stray current issue and the best way to foresee its effects, thereby developing a plan of control and mitigation. A stepwise process is developed for achieving uniform stray current isolation and quality control for all forms of tracks using the data collected from the literature research, U.S. and international transit agency interviews, meetings with corrosion consultants, and stray current testing observations.

Chapter 5 summarizes the review of work done, presents conclusions drawn and objectives achieved, and describes potential future work.

Appendices A through E present a short survey, responses from transit agencies, a long questionnaire, responses from transit agencies, and a decision matrix.

# Introduction

Stray current and stray current–induced corrosion have been causes of concern among transit agencies, electrolysis committees, utility owners, providers, and electric railway carriers not only in the United States but also throughout the globe. With initial principles and mitigation methods dating back to the early 1900s, the first preliminary report on stray current corrosion and mitigation in the United States was prepared in 1916. The document was published as a progress report after the end of the World War I in 1921 (1). To date, most of the principles identified and the mitigation measures recommended in the 1921 electrolysis report are still adopted by transit service providers, the engineering community, and corrosion consultants.

Stray current leakage and the corrosion caused by these currents is more of an issue in low resistivity soils and embedded tracks, which typically run through major traffic areas, city centers, and threads between utility lines that require the rail to be continuously isolated to provide superior track-to-earth resistance (2). Conversely, ballasted tracks have relatively minimal stray current leakage because the entire rail does not require continuous isolation from earth, and separation is needed at the contact points, which are mostly insulated.

Maintenance, periodic testing, and quality control (QC) of stray current control (SCC) still remains an issue, as does the introduction of standardized guidelines to mitigate and collect stray currents. A general understanding in the engineering and the transit communities is that due to the lack of technical guidelines, proper maintenance, and testing procedures the approach to address stray current issues in the rail transit industry is more reactionary than preemptive.

A uniform system for rail track isolation supplemented by QC testing and maintenance guidelines would not only help reduce stray current corrosion faced by transit agencies but also would lessen the ever-rising cost of corrosion repairs to DC-rail transit systems. Much of this repair cost is associated with the restorations performed either to the DC-running rail itself or to the neighboring infrastructure elements such as utilities (3, 4).

The absence of specific national SCC or mitigation standards or guidelines in the United States necessitates the need to produce contemporary standards and guiding principles for transit providers and corrosion consultants.

Real case studies on issues related to stray current effects from transit agencies were used in preparing these consolidated guidelines and recommendations. Some of the case studies involved the following:

- Stray current analysis of national and international transit agencies, which includes European transit agencies, an Australian transit agency, and a Southeast Asian transit agency.

## 4 Stray Current Control of Direct Current-Powered Rail Transit Systems: A Guidebook

- Analysis of stray current corrosion and damage to neighboring utilities from the operation of multiple national and international agencies.
- Review and participation in national and international transit agency maintenance and testing programs.

This TCRP guidebook is a resource to be used immediately by stray current corrosion consultants, transit agency owners, and corrosion testing and maintenance providers.

## 1.1 Research Methodology

The literature research conducted as part of the guidebook development process helped in achieving an understanding of current industry practices, both national and international, and criteria for the mitigation of stray currents. In the absence of any national standards and guidelines, international standards were studied, especially with respect to their relevance to U.S. transit systems. Figure 1 provides a graphic representation of the approach taken to complete various tasks for the research carried out under TCRP Project D-16.

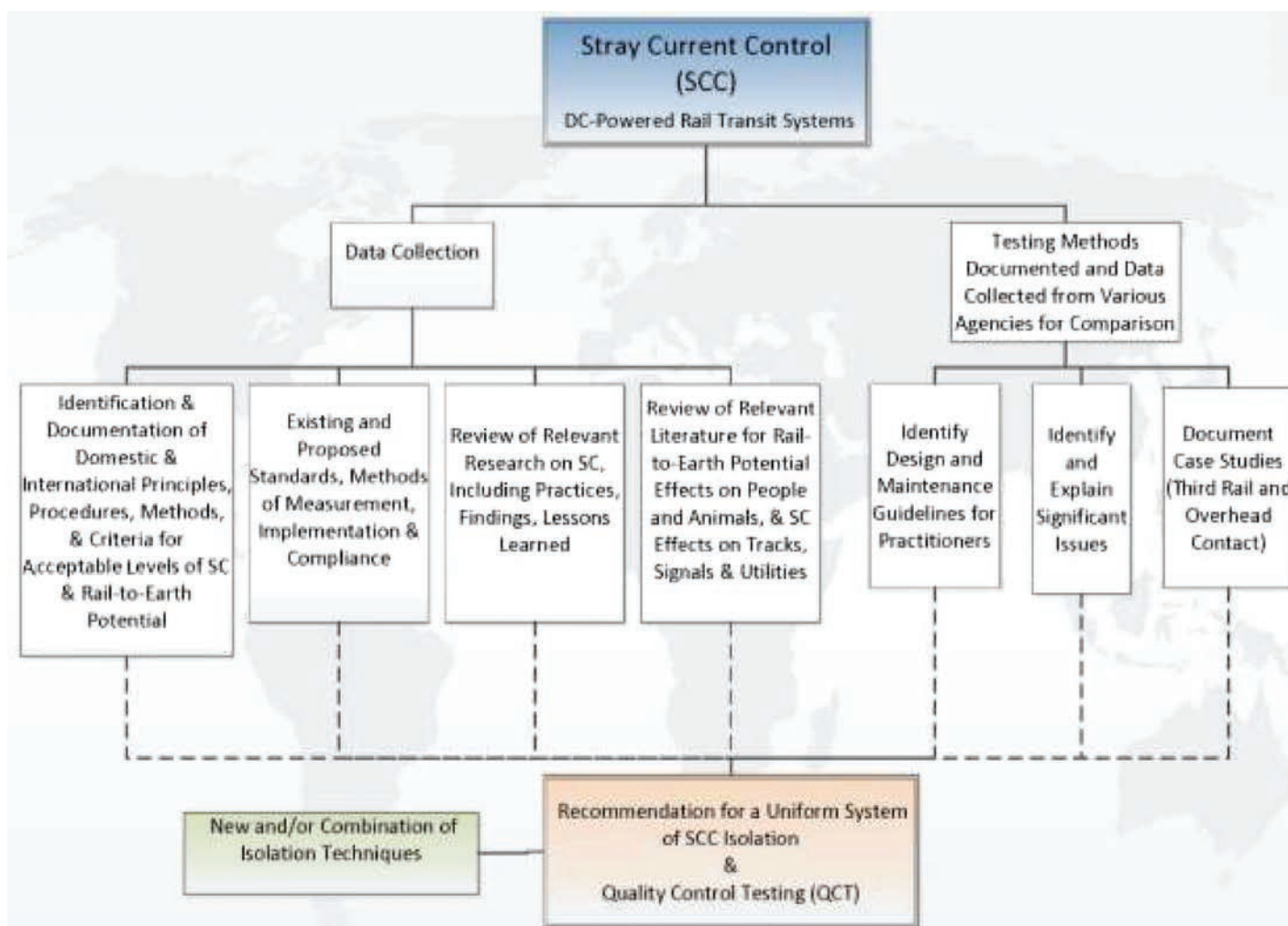


Figure 1. Process layout for SCC research.

## 1.2 Clarification of Terms

The following list presents and defines some terms used throughout the guidebook to avoid confusion in later discussions throughout the chapters.

**Anode.** The electrode of an electrochemical cell at which oxidation occurs (loss of electrons). Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

**Ballasted rail.** Area where the running rails are laid above the ballasted track surface.

**Bond.** The bond is a metallic or reinforced concrete structure made electrically continuous by welding the appropriate components and/or by installation of cables between components to provide a path for the stray current to return to its source without damage to the structure.

**Cathode.** The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

**Cathodic protection.** Electrochemical immunity produced by an appropriate cathodic polarization.

**Conductive part.** Part that can carry electric current.

**Contact line system.** Support network for supplying electrical energy from substations to electrically powered traction units that covers overhead contact line systems and conductor rail systems. The electrical limits of the system are the feeding point and the contact point to the current collector.

**Corrosion.** Progressive degradation or deterioration of a material commonly referred to as rusting, due to its interaction with the environment, that is, air, water, or soil.

**Cross bond.** Electrical connection intended to connect in parallel the conductors of the return circuit.

**Direct drainage bond.** Device that provides electrical drainage by means of a direct bond between an affected structure and the stray current source. The bond may include a series resistor.

**Drainage.** Conductance of electric current from an underground or submerged metallic structure by means of a metallic conductor.

**Drainage bond.** Transfer of stray current from an affected structure to the current source by means of a deliberate bond.

**(Forced) drainage bond.** Device that provides electrical drainage by means of a bond between an affected structure and the stray current source. The bond includes a separate source of DC power to augment the transfer of current.

**(Unidirectional) drainage bond.** This type of drainage bond will include a diode to ensure that the current flows in one direction only.

**Dynamic stray currents.** Stray currents that continually vary in amplitude and/or continually change their electrolytic paths, such as DC-powered mining operations, DC welding equipment, railway systems, and lightning.

**Earthing.** Connection of conductive parts to an appropriate earth electrode

**Electric traction system.** Electrical distribution network used to provide energy to rolling stock.

**Electrolysis.** Production of chemical changes of the electrolyte by the current flowing through an electrochemical cell.

**Embedded rail.** Area where the top of the running rails is at the same level as the surrounding surface.

**Equipotential bonding.** Provision of electric connections between conductive parts, intended to achieve equipotentiality.

- Fault condition.** Non-intended condition caused by short-circuit.
- Fourth rail.** Conductor rail used instead of the running rail for the return currents.
- Galvanic corrosion.** Accelerated corrosion of a metal because of an electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte.
- High voltage.** Nominal voltage exceeding alternating current (AC) of 1,000 volts or DC of 1,500 volts.
- Indirect contact.** Electric contact of persons or animals with exposed conductive parts that have become live under fault conditions.
- Isolating joint.** A joint that breaks electrical continuity in a structure but does not affect the mechanical integrity of the structure.
- Insulating rail joint.** Mechanical rail joint that longitudinally separates the rail electrically.
- Low voltage.** Nominal voltage up to and including AC of 1,000 volts or DC of 1,500 volts.
- Overhead contact system.** Electric contact system using an overhead contact line to supply current for use by traction units or rolling stock.
- Polarization.** The change from the open-circuit potential resulting from current across the electrode/electrolyte interface.
- Potential shift.** A change in measured potential of a metallic structure caused by the application of current from an external source.
- Rail potential.** Voltage occurring between running rails and earth.
- Rail-to-earth resistance.** Electrical resistance between the running rails and the earth or structure earth.
- Rail-to-rail cross bonding.** Electrical bond that interconnects the running rails of the same track.
- Return circuit.** All conductors that form the intended path for the traction return current to the substation.
- Return conductor.** Conductor that parallels the track return system and connects to the running rails at periodic intervals.
- Short circuit.** Accidental or intentional conductive path between two or more conductive parts forcing the electric potential differences between these conductive parts to be equal to or close to zero.
- Static stray currents.** Stray currents that maintain constant amplitude and constant paths, such as high voltage DC power transmission lines.
- Stray current.** Part of the current caused by a DC-traction system that follows paths other than the return circuit.
- Stray current corrosion.** Corrosion resulting from stray current leakage.
- Telluric current.** An electric current that moves underground or through the sea. Telluric currents are phenomena observed in the earth's crust and mantle.
- Third rail/conductor rail.** Rail mounted on insulators located parallel to the running rails to provide the positive feed to the transit vehicle.
- Touch potential.** Voltage between the energized object and the feet of a person in contact with the object. It is equal to the difference in voltage between the object and a point some distance away.
- Touch voltage.** Voltage between conductive parts when touched simultaneously by a living object (person or an animal).
- Track circuit.** Electrical circuit, of which the rails of a track section form a part, with usually a source of current connected at one end and a detection device at the other end for detecting whether this track section is clear or occupied by a vehicle.
- Track return system.** System in which the running rails of the track form a part of the return circuit for the traction current.
- Track-to-track cross bonding.** Electrical bond that interconnects tracks.

**Traction power.** Propulsion power for rail transit vehicles.

**Traction power substation.** Installation to supply a contact line system with power. The substations may convert energy from a utility to the form that matches the transit vehicles' needs.

**Traction return current.** Sum of the currents returning to the supply source, the substation, or regenerative braking vehicles.

**Voltage limiting device.** Protective device whose function is to prevent existence of an impermissible high touch voltage.



## CHAPTER 2

# Literature Review

A literature review was conducted to identify the body of knowledge, both domestic and international, which pertains to principles, procedures, methods, and criteria for achieving, documenting, and maintaining acceptable levels of stray current. This review will help the reader understand stray current, the process of its evolution, the associated corrosion, and the mitigation methods from the early days of the introduction of electrified rail systems to present-day design.

The literature and articles reviewed date back to 1916 (5) and cover a range of national and international findings on this topic. The literature research includes the study of technical journals, conference papers, books, design criteria documents from transit agencies, and the review of significant related articles and reports by research institutes and agencies or organizations. The list of various public and private agencies and sources includes, but is not limited to: the Transportation Research Board; the Transportation Technology Center; the Transit Cooperative Research Program; the American Public Transportation Association (APTA); the American Railway Engineering and Maintenance-of-Way Association (AREMA); Unified Facilities Criteria; and Australian, European, and South Asian Standards. The corrosion control criteria documents from various national transit agencies were used to develop a platform for comparative analysis and standard comparison. Some of the reports, in particular TCRP reports, gave an insight to a wealth of unparalleled history and background information on track-related research (6), rail base corrosion detection and prevention (7), and light rail transit design (8).

In the United States, the Corrosion Society published recommendations on mitigation methods in the form of a report in 1921 (1). This report included some detailed mitigation techniques and construction methods. These techniques and methods were based on the study of transit systems at that time in Europe and America and included the following countries:

- Germany—Earth Current Commission’s Recommendations (recommendations as adopted by the gas, water, and railway interests of Germany in 1910–1912).
- France—Regulations by the Minister of Public Works (1911).
- England—British Board of Trade Regulations (1894–1912).

After reviewing recommendations from the previously mentioned countries and the research conducted by the local transit agencies in the United States, the Corrosion Society suggested that further testing and guidelines were warranted. Nothing substantial was done, however, until the 1950s and then the 1960s when the sensitivity of the stray current topic increased again (3). The 1960s was followed by another period in the 1980s and 1990s, when the National Aeronautics and Space Administration’s Technology Utilization and Industry Affairs Division conducted a research project for the U.S. Department of Transportation and

produced a manual on corrosion control (9) and the first reference book (10). This reference book presents a compilation of more than 30 technical papers on stray current corrosion until 1994.

The literature review conducted for TCRP Project D-16 provides a synopsis of the technical methods used to control stray current over the years and the recent advancements nationally and internationally. The literature review has shown that stray current is not as significant an issue in AC-traction power as it is in the DC-powered traction system (11), which is usually supplied by the overhead catenary system or the third rail. The following text summarizes the various concepts and topics covered under the literature review.

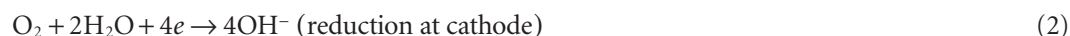
## 2.1 Corrosion and Corrosion Rate

Corrosion could be defined as the deterioration of a material, commonly referred to as rusting (primarily when the metal is steel and iron), due to its interaction with the environment, that is, air, water, or soil. The practical definition is the tendency of the metal to revert to its natural oxide state (12). In simple terms, the corrosion process is a natural chemical or electrochemical reaction between a metal and its surroundings, in which the metal is oxidized (loses electrons), resulting in its progressive degradation. The corrosion tendency varies for different metals due to the varying energy content of the elements in their metallic state and is highly dependent on the surrounding environment.

The process of corrosion requires four elements: electrolyte, anode, cathode, and a metallic path. Oxidation (loss of electrons) takes place at the anode-forming ions while reduction (gain of electrons or decrease in oxidation state) takes place at the cathode, which causes the anode to dissolve while the cathode remains intact. Electrolyte is defined as a solution of acids, bases, or salts containing free ions through which the electric current flows.

The process of corrosion involves more than one oxidation and one reduction reaction (also referred to as anodic half-reaction and cathodic half-reaction). At least one such reaction must take place at the anodic surface for corrosion to occur so that the ions are formed and electrons are released. In case of electrolysis of underground structures, the moisture in the soil along with its dissolved acids, salts, and alkalis acts as the electrolyte, whereas electrodes are the metal utility pipes (13).

Equations 1 and 2 represent a typical anode and cathode reaction, in which oxidation occurs when current leaves the rail to earth (anode reaction), whereas reduction occurs when current returns to the rail (cathode reaction):



where  $M$  is the element involved (steel) and  $e$  is electrons.

For corrosion to take place, both reactions need to occur at the same time. Checking if the damage is caused by a uniform attack or a localized attack measures the level of corrosion. In a uniform attack, the mass of metal corroded per unit of the surface area will define the damage, whereas in a localized attack the depth of penetration on a metal will define the corrosion rate (12). Corrosion rate is a function of many variables and thus in most cases it cannot be calculated without making some assumptions. The corrosion rates can be calculated using Faraday's law by measuring the corrosion current flowing between the anode and cathode (the two ends) of the metal. Though the laws of physics for stray current corrosion are the same

as those for galvanic corrosion, the metal loss is much faster due to the large amount of stray current leakage (14). See Equation 3.

$$\text{Corrosion\_rate} = \frac{I_{\text{corr}}}{nF} \quad (3)$$

where

$I_{\text{corr}}$  = corrosion current density in  $A/m^2$ ,  
 $F$  = Faraday's constant 96,490 C/mole (Coulombs per mole of electrons), and  
 $n$  = number of electrons transferred per molecule of a metal corroded.

To put things into perspective, one ampere of DC current that is constantly flowing from a metallic structure for 1 year will result in the dissolution of 20 pounds of iron, 75 pounds of lead, 22 pounds of copper, or 6.5 pounds of aluminum (15). To illustrate, the electrical decomposition of iron was calculated in Equation 4 by using Faraday's Law (11) as

$$\text{Faraday's Law: } m = (Q/F)(M/n) \quad (4)$$

where

$m$  = mass of substance liberated in grams (g),  
 $Q$  = total charge transferred in the reaction in Coulombs (C),  
 $M$  = molar mass of the substance in g/mole ( $M$  for iron = 55.845 g/mole), and  
 $n$  = number of electrons transferred per molecule of a metal corroded ( $n$  for iron = 2).

One ampere will be equivalent to a flow of 1 Coulomb of charge per second ( $1A = C/s$ ). Assuming mass of iron altered due to the flow of one ampere of stray current for a year and using the number of seconds in a year ( $Q = It$ , where  $I$  is the current in amperes and  $t$  is time in seconds), the resultant loss in mass of iron comes out to be 20.1 pounds (9,126 grams).

From a practical viewpoint, it is not so much the total DC current that is important for the severity of corrosion but the local current density, because it is the local attack causing reduction in strength of structural members more than the uniform corrosion. Experimental studies have shown the effect of current density and duration of current discharge on corrosion of reinforcing steel and prestressing steel.

According to a 2001 study supported by the Federal Highway Administration (FHWA) and the National Association of Corrosion Engineers (NACE), the annual cost of metallic corrosion in the United States is \$276 billion. Only part of this cost is directly attributable to stray current corrosion. Significant savings can be achieved if proper inspection and corrosion management practices are employed (16).

For the reliability and safety of public infrastructure, productivity of systems, minimal impacts to the environment, and economic competitiveness, it is essential to understand the fundamental cause of corrosion. Once understood it is possible to find the most effective options for corrosion mitigation and to generate best guidelines and principles along with regular inspection techniques.

There are many forms of corrosion depending on the type of metal, the surrounding environment, and the length of exposure to the environment; however, this guidebook will focus only on the types of corrosion caused by stray current from the DC-powered transit system.

Though DC-electrified transit systems are the main cause of stray current, there is another form of stray current called telluric currents. Telluric currents are caused by transient

geomagnetic activity. The influence of telluric currents on structures is for a limited duration due to nonlocalized discharge areas and thus is rare to find. Likewise, currents caused by other systems and operations are not discussed further in this guidebook, and the focus is on stray currents caused by the DC transit system.

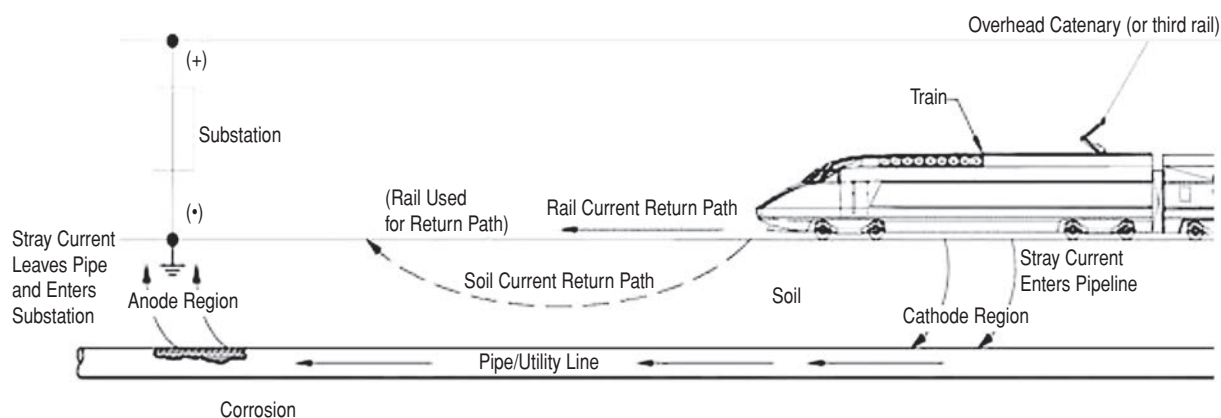
## 2.2 Stray Current and Stray Current Corrosion by Transit Systems

The operating current for the electric traction power supply flows through the overhead catenary system or the third rail to the vehicle and returns to the substation through the return circuit. The return circuit includes numerous conductors that help complete the path of the return current to the substation. Running rails are the most widely used conductors for the return of electric current. Since perfect insulation does not exist and rails have finite resistance, the return current leaks into the earth and finds its way to the substation via the path of least resistance. A handful of transit systems use a fourth rail system for the return of current, which is typically an insulated conductor fourth rail, electrically isolated from the running rails and the surrounding soil. This fourth rail collects the current and returns it to the substation.

The alternative paths of least resistance that the return current may take include metallic utility lines, other metallic structures, reinforcement in the slab structure, and the soil itself. This current that takes the path of the least resistance (other than the rail) is called stray current and can be defined as the current that flows in the unintended path. Stray current corrosion is the corrosion that this stray current causes along its path (Figure 2).

In a DC-powered rail transit system, stray current will follow any path of least resistance on its way to the traction power substation (TPS). This causes extreme corrosion to the metallic structures where it leaves the conductor. Hence, when there is a continuous flow of electric current, measures need to be taken to contain it at the source by providing suitable insulation or by using other means of rail isolation. This will prevent the current from flowing into the conductor earth.

Stray current affects all the metallic components that are under the track, including the reinforcement steel supporting neighboring structures and rail track metallic components. Risk of stray current flow from the rail to other metal structures is greater when the potential difference between the rail and other metals is higher, which occurs in low resistivity soils.



**Figure 2.** Stray current corrosion path.

To reduce this stray current, the rail-to-earth potential should be as uniform as possible over the entire length of the utility pipeline and the utility line needs to be electrically continuous (8).

Stray currents are hard to detect since they are irregular because of varying dynamic rail traffic. The conventional method is to record the pipeline potential in the suspect areas for at least 24 hours. Corrosion rate depends on the current level (intensity), duration of current, and the properties of the metal. Figure 3 is a simple circuit model demonstrating the basic components affecting the levels of stray currents generated by a DC traction power system (17). The components within the simple circuit model include the following:  $R_N$  is the resistance of negative return circuit,  $R_p$  is the resistance of positive circuit,  $R_L$  is track-to-earth resistance at the load end,  $R_S$  is track-to-earth resistance at the source end,  $I_T$  is train operating current,  $I_N$  is current return through the rails,  $I_L$  is leakage current to earth at the load end,  $I_S$  is current returning to substation through earth,  $V_S$  is substation voltage,  $V_{GL}$  is track-to-earth voltage at the load end,  $V_{GS}$  is track-to-earth voltage at the substation location, and  $V_N$  is voltage developed across  $R_N$  by  $I_N$ .

Equations 5, 6, and 7 present the relationship between the voltages  $V_{GL}$ ,  $V_{GS}$ , and  $V_N$ .

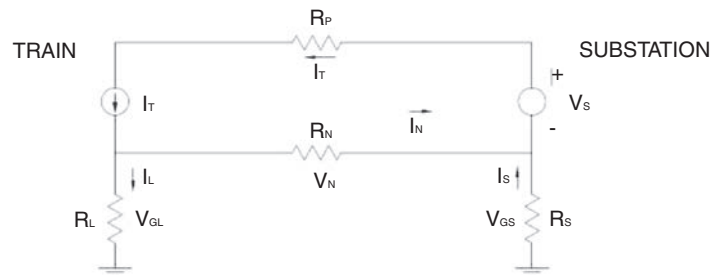
$$V_{GL} \approx \frac{R_L}{R_L + R_S} \times V_N \quad (5)$$

$$V_{GS} \approx \frac{R_S}{R_L + R_S} \times V_N \quad (6)$$

$$V_N = I_N \times R_N \quad (7)$$

Corrosion rate is directly proportional to stray current and is more severe when focused on a small area. Unlike natural corrosion, however, stray current corrosion is independent of oxygen concentration and pH and is mainly related to the DC currents from rail transit (18). Although generally referred to as electrolysis, it is the process whereby chemical changes take place in the electrolyte when DC flows through a metal. The entire process of corrosion of underground metals is accelerated because of stray current. Rail-based corrosion gets worse (expedites) due to electrolysis caused by DC at the contact point with wet debris (mud or slime) that builds up under the rail base and also due to deicing salts (7).

Stray current not only corrodes neighboring utilities but also affects the metallic structure of the transit system itself. Based on a 1990 report prepared and provided by NACE, Battelle Memorial Institute, and the U.S. Department of Commerce, the cost of corrosion caused by stray current was estimated to be \$500 million annually (19). This number does not take into account the costs associated with signal problems and primarily accounts for the losses



**Figure 3. Simple circuit model illustrating stray current components (17).**

**Table 1. Estimated stray current leakage (in amps) by a transit system (20).**

Track-to-Earth Potential (volt)	Track-to-Earth Resistance [ohms – ( $\Omega$ )] per 1,000 ft. (305 m) of Track (2 Rails)						
	10	25	100	250	500	1,000	12,500
10	2.000	0.800	0.200	0.080	0.040	0.020	0.002
20	4.000	1.600	0.400	0.160	0.080	0.040	0.003
30	6.000	2.400	0.600	0.240	0.120	0.060	0.005
40	8.000	3.200	0.800	0.320	0.160	0.080	0.006
50	10.000	4.000	1.000	0.400	0.200	0.100	0.008
60	12.000	4.800	1.200	0.480	0.240	0.120	0.010
70	14.000	5.600	1.400	0.560	0.280	0.140	0.011
80	16.000	6.400	1.600	0.640	0.320	0.160	0.013
90	18.000	7.200	1.800	0.720	0.360	0.180	0.014
100	20.000	8.000	2.000	0.800	0.400	0.200	0.016

to DC-powered transit agencies and detrimental effects to surrounding infrastructure and utilities. A recent TCRP study in 2007 on “rail base corrosion detection and prevention,” suggests that the steel used in the fabrication of rails can hold up to the effects of the environment (galvanic corrosion); however, DC significantly affects the corrosion rate and makes the rails less corrosion resistant (7). Table 1 shows an estimated average stray current leakage by a transit system.

## 2.3 Traction Power

Transmission of electric power has always been along the track by means of an overhead wire (see Figure 2) or at ground level by means of a third rail mounted on the insulators (extra rail) close to the running rails. (Safety concerns about a ground-level third rail are not discussed.) AC systems use overhead wires whereas DC systems can use either an overhead wire or a third rail; both are common. Current supplied to the train from the substation depends on the size and the number of train cars. Both AC and DC overhead systems require at least one collector attached to the train so it can always be in contact with the power supply. With economics and cost being the deciding factors in the selection of the train’s circuit return path, running rails have been used in most rail transit systems as the return conductor for the return of traction power to the substation. The running rails are at earth potential and connect to the substation.

There have been long, ongoing debates since the inception of electric traction on which supply system is better, AC versus DC. The scope of this report is not to determine whether a DC or AC transit system is better; however, it is worthwhile to understand the basic variation between the two systems. The general rule has been that AC is for longer distance commuter and high-speed rails, whereas DC traction is used for shorter distances like metropolitan and suburban lines. In the early days, the AC-powered vehicle had to carry a transformer onboard to convert the high voltage to a lower system voltage. This transformer was quite heavy and therefore for smaller trains carrying smaller passenger capacities, it was inefficient in terms of weight per vehicle. However, the introduction of AC motors around 1965 eliminated the issue of converting the current into DC (21).

For DC trains, the transformer is located at the substations, along with the rectifier, to supply DC power, thus increasing the efficiency of the vehicle, which represents a balanced weight/cost versus passenger capacity for short distances and makes it reliable as there is less equipment to fail. Throughout the globe, over half of all electric traction systems still use DC (21). However, based on the literature reviewed so far and on the advancements made in traction power, AC traction power is the preferred current in countries building new rail systems, including

**Table 2. Comparison of traction power systems.**

AC Traction Key Factors	DC Traction Key Factors
Draws unbalanced power from two of the three phases.	Draws balanced power from the utility supply.
Train Handling	Purchase Cost
Delivers traction power at higher voltage, which then <ul style="list-style-type: none"> <li>delivers power over longer distances and</li> <li>allows for less frequent substations.</li> </ul>	Delivers traction power at low voltage, which then <ul style="list-style-type: none"> <li>allows for tighter clearance and</li> <li>requires more frequent substations.</li> </ul>
Challenged by its need to receive power from high voltage.	Challenged by stray current.
Ease of maintenance	

high-speed lines, primarily due to much higher reliability and reduced maintenance requirements of AC traction motors (21). A high voltage direct current transmission system has been used for economy and power flow control but has yet to be used for a rail transit system.

Some of the commonly used and proven traction systems in use by transit systems are the following:

- DC 600 volt, 750 volt, 1,500 volt, and 3,000 volt overhead catenary;
- DC 600 volt and 750 volt third rail; and
- AC 16.7 hertz 15 kilovolt and 50 hertz 25 kilovolt overhead catenary.

Table 2 illustrates some of the common advantages and disadvantages of both power systems based on the literature search.

It is important to mention here that although this study focused on the damage caused by DC, leakages of AC at industrial facilities have also been suspected to corrode buried metallic structures. The general perception among corrosion engineers is that corrosion caused by AC is less severe than corrosion caused by DC. Thus, the possibility of damage to any metallic utility line resulting from AC corrosion seems small.

## 2.4 Soil Resistance—Corrosion and Earth Conduction

A mitigation method in minimizing stray current leakage is to keep the rail-to-earth resistance high by electrically insulating the rail from the surrounding pavement/earth especially through urban/suburban streets and pedestrian crossings. This insulation inhibits the stray currents from entering the soil and causing corrosion of metals in the surrounding structures.

Soil resistivity is used to gauge the degree of corrosion in underground utility lines. The literature review demonstrates that areas with low earth resistivity values result in an increased corrosion risk affecting metal pipes and other infrastructure in the absence of any stray current mitigation and collection system (13). In comparison with other conductors like copper and steel, earth is a poor conductor of electricity. However, it will change to a good conductor provided the area of the path of the current is large, which in turn lowers earth's resistance. The resistance of the surrounding earth will generally be larger than the pipe resistance and the pipe-to-earth resistance and is heavily dependent on the soil type, temperature, and moisture content.

Though resistivity of soil changes with the type of soil, it is difficult to give an exact value of soil resistivity and thus soil resistivity is defined in a wide range of values (see Tables 3 and 4). The amount of moisture content, soil content, and chemical constitution drastically affects soil's resistivity (22). This includes the effects of chlorides and sulfates on soil caused by the deicing

**Table 3. Soil resistivity range (22).**

Soil Description	Average Resistivity, ohm-cm (range)
Well-graded gravel, gravel–sand mixtures, little or no fines	60,000–100,000
Poorly graded gravels, gravel–sand mixtures, little or no fines	100,000–250,000
Clayey gravel, poorly graded gravel, sand–clay mixtures	20,000–40,000
Silty sands, poorly graded sand–silts mixtures	10,000–50,000
Clayey sands, poorly graded sand–clay mixtures	5,000–20,000
Silty or clayey fine sands with slight plasticity	3,000–8,000
Fine sandy or silty soils, elastic silts	8,000–30,000
Gravelly clays, sandy clays, silty clays, lean clays	2,500–6,000 <sup>a</sup>
Inorganic clays of high plasticity	1,000–5,500 <sup>a</sup>

<sup>a</sup>These results are highly influenced by the presence of moisture.

salts found on the track. For most soils, the pH value falls within the range of 5 to 8 and is generally not considered to be the dominant variable affecting corrosion rates (though higher acidic soils present serious corrosion risks) (7). An increase in temperature will also decrease the resistivity of soil whereas the resistivity will increase as the temperatures fall below freezing. This seasonal variation makes it difficult to assume a fixed value for earth's resistivity and the only safe way to establish the correct resistivity values is to measure them.

Resistivity of the soil is a significant factor in the determination of the most effective and efficient stray current collection system. Since so many elements factor into the resistivity of the soil, including temperature, soil resistivity studies must be performed and a worst-case scenario should be used for the design of a collection system. The allowable earth potential gradient development over a given length from the rails is determined by using the soil resistivity levels. The resistance ( $R$ ) of any system of electrodes to earth can be theoretically calculated by Equation 8 (22):

$$R = \rho L / A \quad (8)$$

where

- $\rho$  = the resistivity of the earth in ohm-cm,
- $L$  = the length of the conducting path, and
- $A$  = the cross-sectional area of the path.

Additionally, the four-point method, also known as Wenner's method, is the most commonly utilized method, depending on the depth, to determine the soil resistivity ( $R = \rho / 2\pi a$ ) (23).

A study by Pham et al. in 2001 presented an earth potential gradient model that measures the potential developed between two points in the earth. The magnitude of this

**Table 4. Corrosivity ratings based on soil resistivity (7).**

Soil Resistivity, Ohm-cm (range)	Corrosivity Rating <sup>a</sup>
>20,000	Essentially noncorrosive
10,000–20,000	Mildly corrosive
5,000–10,000	Moderately corrosive
3,000–5,000	Corrosive
1,000–3,000	Highly corrosive
<1,000	Extremely corrosive

<sup>a</sup>Particularly to chloride and sulfates.

potential will have a direct link to the stray current effect on buried utilities. The earth potential gradient is calculated by using Equation 9 (17):

$$E = \frac{\rho I}{\pi l} \cdot \ln \frac{d_1}{d_2} \quad (9)$$

where

- $I$  = current from source (amperes),
- $d_1$  = distance from source of structure,
- $d_2$  = distance from source of structure, and
- $l$  = length of current source (parallel rail), cm.

Equation 9 has the following limitations, as acknowledged by the authors:

- Soil resistivity is assumed uniform within the length.
- Earth potential gradients are assumed not to be distorted due to the presence of pipes and are unchanged between any two points.

Occasionally chemical treatment of the soil is carried out before construction of the tracks to stabilize the soil resistivity and to provide a stray current collection system. Chemicals like sodium chloride, magnesium sulfate, copper sulfate, and calcium chloride have been known to have been used temporarily in the past to reduce the soil resistivity. A reduction of resistivity by 15% to 90% depending on the type of soil could be achieved by chemical treatment. This treatment is carried out mostly on high resistivity soils to ensure an effective low resistance grounding system and/or stray collection system (22).

## 2.5 DC Traction System Grounding (Earthing)

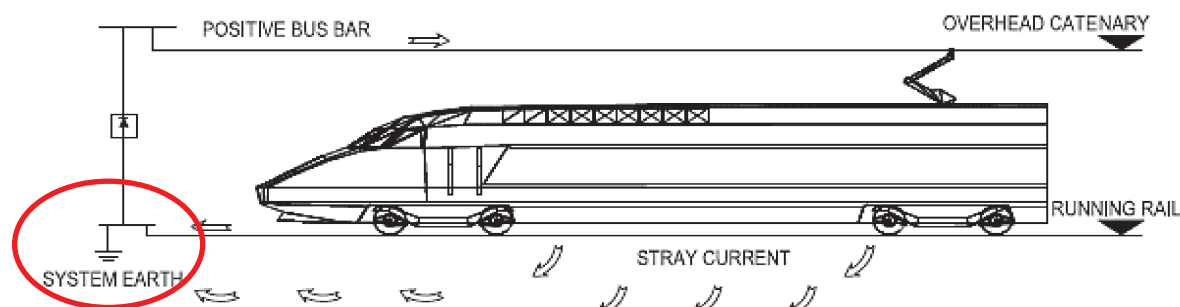
DC traction power design includes three different earthing systems: the solidly bonded or grounded, the floating or ungrounded, and the diode-bonded systems. Most of the older transit systems used the solidly grounded system; however, the literature research that follows shows that it caused more problems than it solved. Consequently, floating, automatic grounding systems, and diode-bonded systems, emerged to satisfy the conflicting requirements of stray current and touch potentials. In a DC traction system, however, it is still a challenge to completely stop stray current leakage and reduce the rail voltage at the same time. Thus, a suitable traction power design and selection of an appropriate grounding scheme are essential to reduce the rail voltage and the stray current leakage.

To have a clear understanding of the subject it is important to realize the difference between system grounding and equipment grounding. *System grounding* refers to grounding of current conductors of the DC negative return system whereas *equipment grounding* refers to the grounding of enclosures of the rectifier unit and DC switchgear (24). Equipment grounding is not within the scope of this literature review.

The main objective of system grounding for all the transit systems is to offer the continuity of a safe power supply. This includes not exposing any human being to electric shock in the vicinity of the earthen installation and minimizing DC stray current during normal and fault conditions. To achieve this objective, transit agencies use the following grounding methods along with their limitations.

### 2.5.1 Grounded or Solidly Bonded System

A grounded or solidly bonded system is characterized by the direct metallic connection of the rectifier negative bus to the local ground grid at the substation. Absence of insulation on



**Figure 4. Grounded or solidly bonded system.**

the running rails is an optional characteristic. This system permits the unregulated flow of stray current where stray currents will leave the running rails along the entire length and will return at the substation ground grid using paths other than the running rails. This leakage of stray current increases the potential of corrosion and thus this system is not used in modern DC transit systems. See Figure 4.

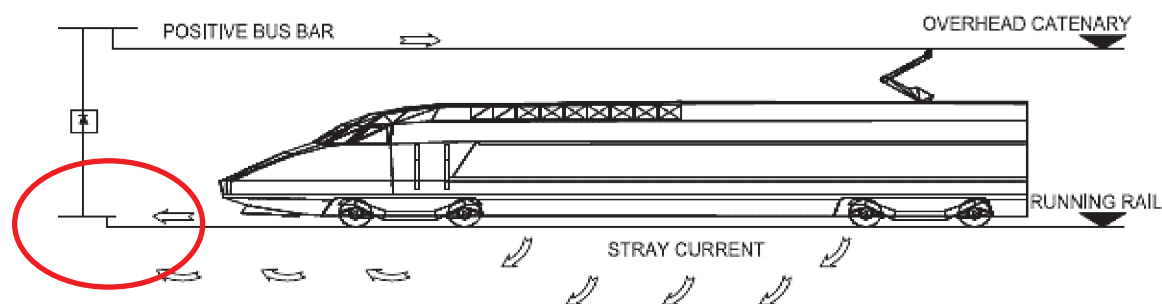
### 2.5.2 Ungrounded or Floating System

Unlike a grounded system, a floating system has no deliberate connection to earth and thus represents the other extreme of traction power design. High rail-to-earth resistance using rail boot, rail coating and rail fasteners restricts stray current. However, this could potentially result in increased running rail voltage, as compared with the grounded system, causing safety concerns for the public and transit agency staff. Moreover, during fault conditions, high electric potentials can develop between the platforms and the earth. Though these safety concerns present a downside to the system, this system is preferred over the other systems, and concerns have been addressed with the use of overvoltage protection equipment and platform insulation procedures. See Figure 5.

### 2.5.3 Diode-Grounded System

In a diode-bonded system, the traction power substation is connected to the ground grid through a diode arrangement and stray currents can be collected (collection mat) and returned to the substations via the diode path. This system represents a compromise between grounded and ungrounded systems and is used to alleviate the problems in old grounded systems.

In this system, the diode, in the negative return ground connection, will provide a low resistance path to permit the faster clearing of the fault currents. However, this also permits stray



**Figure 5. Ungrounded or floating system.**

currents to return to the substation via the diode path, which can potentially increase stray current corrosion. Diode systems provide a unidirectional flow. This essentially means that they block the flow of current from the negative bus to the ground grid or collection mat. However, they allow the fault currents and the rail leakage currents back to the substation. Research shows that diode-earthing system may result in high touch potentials and stray currents at the same time (25). See Figure 6.

### 2.5.4 Additional Research on System Grounding

A study presented in 2002 provided an account of DC traction power-system grounding practices in North America (24). The study first highlighted the difference between equipment and system grounding and then discussed the stray current leakage and personal safety affected by various system-grounding techniques. In addition to the three system-grounding schemes previously described, the author also presented the “automatic grounding switch” and “thyristor grounding schemes.” Figure 7 represents all the grounding schemes presented in the study.

The thyristor grounding system will work as an ungrounded system under normal system operation and will ground the system only when an unsafe voltage occurs. Unsafe voltages may develop due to either train bunching load currents or due to positive (third rail)-to-earth faults. This gives the thyristor system an edge over a diode-grounded system, since diodes are always conductive (grounded system) under normal system operation and when there are small voltage differences between rail and earth.

A study in 2005 (26) also presented the impacts of different grounding schemes. The study, with the help of a simulation model, demonstrated the advantages of a floating rail system. The study concluded that total stray current leaking from a floating system could be “four times” less than that in a grounded system. The authors highlighted the need to take steps to maintain safe levels of rail-to-earth voltages during fault conditions for the floating system.

Two additional papers on the Taipei transit system published in 2006 (27) and in 2009 (28) carried out a detailed analysis of the grounding schemes and their effects on rail potential and stray currents. Simulation models were used to analyze one of the tracks (Blue line). The authors concluded that general ungrounded systems generate less stray current than diode-grounded systems whereas diode-grounded systems are used to reduce the stray current corrosion issues in old grounded systems.

Based on the findings of the literature review, one can safely conclude that, to date, an optimal earthing setup that would decrease the stray current level and maintain touch potentials within

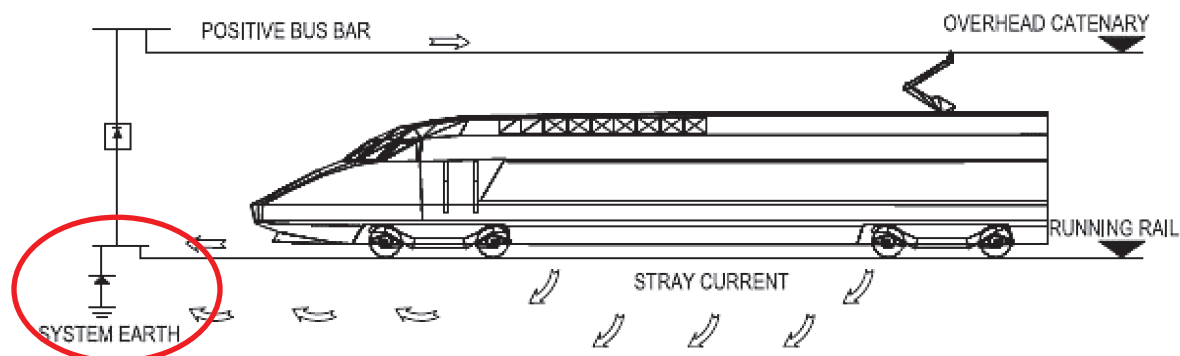
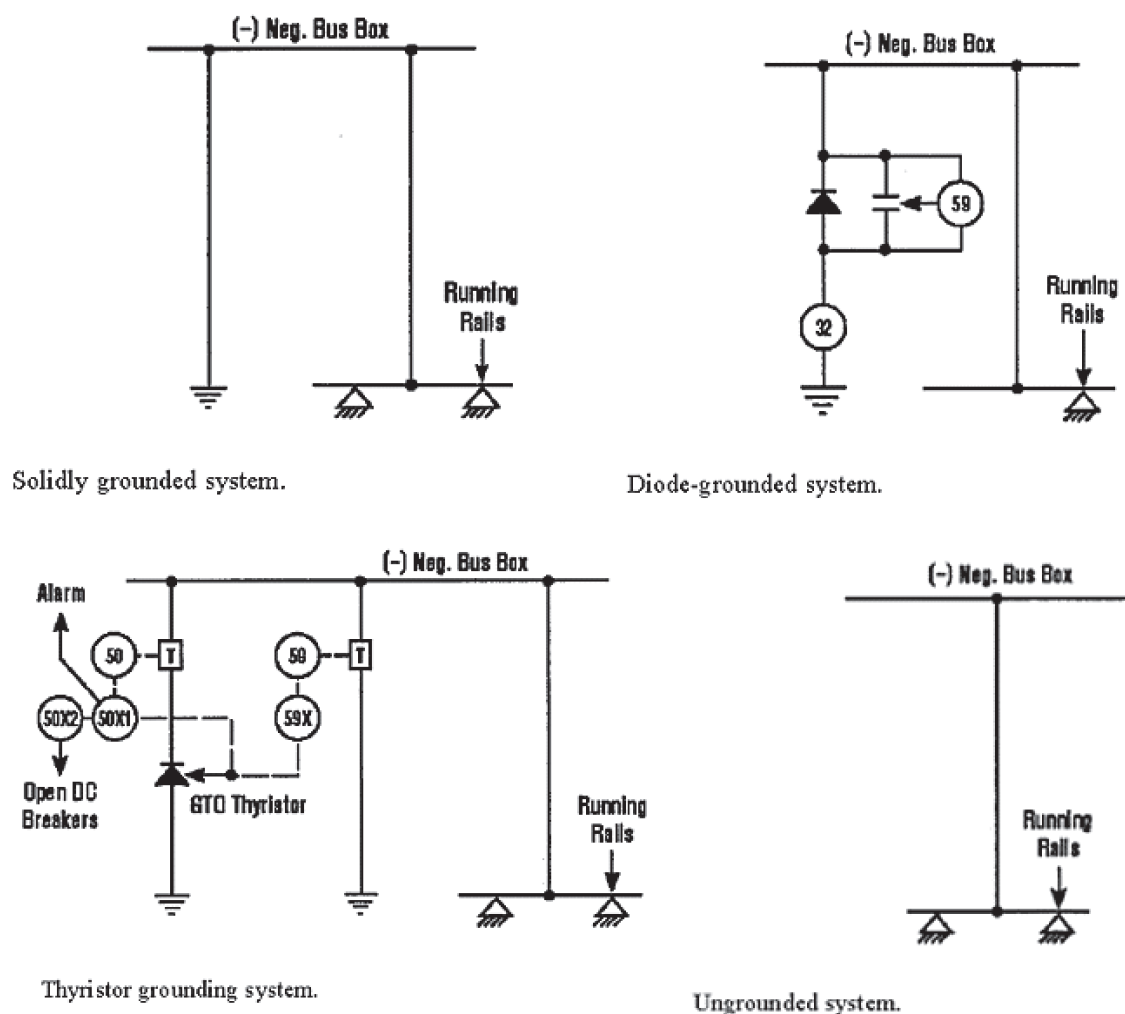


Figure 6. Diode-bonded system.



Solidly grounded system.

Diode-grounded system.

Thyristor grounding system.

Ungrounded system.

Figure 7. Grounding system types (22).

safe limits is yet to be discovered. Numerous studies highlight the advantages and disadvantages of each scheme over the other; however, the effectiveness of grounding systems varies for different systems. Typical examples are two scientific papers presented by engineers of Railway Systems Consultants Ltd. (29), and Balfour Beatty Rail Projects Limited (30). Both studies concluded that the grounding schemes would have to be case specific and tailored to each application and to the dominant conditions.

An optimal earthing setup is another area in which transit agencies need specific standards or guidelines to properly design the traction power system, but this is beyond the scope of this guidebook.

## 2.6 Effects of Stray Current on People and Animals

The running rails of a DC transit system do not connect to structure earth or earth to avoid stray current leakage, which could potentially result in increased touch potentials. The local and time-dependent rail potential is the main reason for touch voltages under operating and fault conditions. Safety practices are followed to prevent electrical shock hazards to personnel who may be exposed to currents during system operation and maintenance and to the public

and animals. To avoid impermissible effective touch voltage, in certain cases, voltage-limiting devices are installed (e.g., at passenger stations) to achieve equipotential bonding between return circuit and earth.

Stray current effects are also considered for the safety hazards they impose on people and animals who come in direct contact or in contact through a conductive part with the affected structure or the connected equipment. The severity of the electrical shock that a person receives depends on several factors such as the potential level and duration of the exposure, the human body and skin conditions, the path and magnitude of the current conducted by the human body, and the general health of the person prior to the shock. The permissible touch voltage therefore is subdivided into long-term values for operation and short-term values for fault conditions, including specific short-term operational situations.

In depots and workshops, protection against impermissible touch voltage can only be achieved by direct earthing of the running rails, which potentially causes stray currents to leak.

## **2.7 History of Stray Current Corrosion and Methods of Mitigation**

Stray current corrosion has been a source of concern for the transit authorities and utility companies since the inception of electrified rail transit systems in the United States. The corrosion problem was originally believed to be caused by a chemical mix of the soil; however, after some research it was evident that the soil alone cannot cause the severe corrosion that was noticed in the rail base and nearby utilities. A conclusion was reached that the leakage of the traction current is the cause of this corrosion. The problem of corrosion caused by stray current in the United States was noticed within 10 years of the first DC-powered rail line in 1888 (31) in Richmond, Virginia. Since then, the control of stray current has been critical in the United States. By that time, Germany, France, and England had also already observed the effects of rail corrosion caused by stray current.

Some of the worst stray current problems are found in the older DC transit systems and are fundamentally due to the following factors:

- Poor insulation of running rails from the earth,
- Improper and wide-spaced substations causing voltage drops in the rail,
- Small rail cross sections of running rails resulting in high electrical resistance, and
- Lack of maintaining a good return system.

The stray current problem is tied to the fundamental design of DC-electrified rail transit systems, in which the running rails and return cables carry the return current to the substations. Considering the magnitude of the stray current corrosion impact, it becomes imperative to provide proper mitigation measures to control the leakage and the upkeep of the tracks by following a maintenance plan.

### **2.7.1 Historical Development**

#### *1890s to 1950s*

To address stray current problems and to provide the best mitigation options possible, during this era corrosion committees and the engineering community conducted numerous studies. Many of those recommendations were implemented on the newer designs at that time, with varying results, including some adverse effects on nearby utility lines, thus making it necessary to conduct further studies. It was in 1921 when some corrosion and engineering solutions

were recommended by the corrosion committee to reduce the leakage and the severity of stray current corrosion. Some of the measures that were successfully developed to control stray current leakage and corrosion follow:

- Use of properly bonded joints (welded joints), cross bonding, and heavy rails for good track conductivity;
- Use of high electrical roadbed resistance to earth and insulated negative return feeders;
- Use of maximum number of traction power substations to reduce the return current distance, consistent with system economy; and
- Use of three-wire traction power system.

These four mitigation and control techniques are described in further detail.

**Bonded joints, cross bonding, and heavy rails.** The use of heavy rail sections and suitably bonded rail joints was one of the earliest implemented mitigation methods for the control of stray current. The evolution of rail sections and steel along with other metal composition has continued throughout the years and across the globe. With time, rail sections have been improved in cross section, length, and the method of joining two sections of rail. With joints being the weak link in the track system, various methods of connecting rail lengths were experimented with before concluding that welded joints provide conductivity equal to or greater than continuous rail and are less subject to failure compared to other forms of rail joints. Thermite welds were the most common kind of welds used by the transit agencies during those times (1).

Welding of rail lengths was thus acquired as the standard form of construction, especially in embedded rails, within the light rail transit systems. This has not only proved instrumental in the reduction of stray current but also improved the performance of rail. Cross bonding between single track and parallel track rails was installed to ensure rail connectivity and to equalize the current flow between the rails, thus reducing voltage drop (rail potential). In the United States, cross bonding was placed at a distance of 500 feet (152 meters) on urban railways and 1,000 to 2,000 feet on suburban railways. In Germany, cross bonds were provided every 328 feet (100 meters). In France, they were placed every 160 to 328 feet (50 to 100 meters) and, in England, they were placed every 120 feet (36.6 meters) (1).

**Resistance to earth and insulation of negative return feeders.** Resistance of the ground immediately in contact with the rail depends primarily on the type of ground material that is in contact with the rail. Measures were taken to insulate the track from the earth to reduce the stray current process, thus reducing the corrosion of the base of the rails and other grounded steel structures for the sections of the rail that were embedded in the ground in urban areas. The corrosion committees suggested maintenance of the tracks to keep vegetation out of the tracks. The committee also suggested maintenance to keep the tracks clean, dry, and dirt and salt free to help keep the resistivity of the rail-to-earth high by keeping them insulated from earth (1).

Well-drained broken stone ballast or gravel ballast was recommended for use in the non-embedded sections for its much higher resistance to stray current as compared with concrete. However, authorities in Germany and England were of the view that leakage of current cannot be reduced by roadbed construction. In the United States, it was recognized that well-drained crushed stone ballast had a resistance from 2  $\Omega$  to 5  $\Omega$  per 1,000 feet of single track. In comparison, the resistance of solid concrete ballast in contact with the rails and also earth roadbeds in which the ties are embedded was only from 0.5  $\Omega$  to 1.5  $\Omega$  per 1,000 feet of single track and 0.4  $\Omega$  for 1,000 feet of double track. Moreover, it was also established that resistance in dry weather may be three or more times higher than in wet weather per 1,000 feet of single track (1).

Non-insulated negative return feeders were widely used in early constructions, especially where track bonds could not be well maintained. Supplementary conductors were installed in parallel with the track and connected to the track at frequent intervals to carry the current to the negative feeders and to ensure continuity of the return circuit. However, it was soon detected that these buried bare conductors increase the contact area between the return circuit and the earth, therefore counteracting the significance of their need (5).

Later it was also deduced that the use of frequent substations along the route provided more economical increase in the track current drainage points compared with the use of insulated negative feeders.

**Maximum number of traction power substations.** Another stray current mitigation technique that saw more advancement earlier on was increasing the number of substations consistent with economy. This technique reduces the feeding distances and the amount of current to be returned to any one point, resulting in the reduction of track voltage drop, thereby reducing the amount of current that will stray away from the rails.

Technology papers by the Bureau of Standards on leakage of currents from electric railways, issued in 1916 (5) explain the importance of reducing the feeding distance to minimize stray current leakage for both grounded and ungrounded systems by using Equations 10 and 11.

$$i = Ae^{\sqrt{\frac{\delta}{r}}(x)} + Be^{-\sqrt{\frac{\delta}{r}}(x)} \quad (10)$$

$$i = Ae^{ax} + Be^{-ax} \quad (11)$$

where  $a = \sqrt{\frac{\delta}{r}}$  and  $A$  and  $B$  are the integration constants.

*Formula for using boundary conditions for ungrounded system:* at the beginning of the line  $x = 0$  and the current  $I = 0$ , whereas at  $x = L$  the current in the tracks must be  $i_o L$ . Thus, the total leakage current up to any point  $x$  can be calculated by using Equations 12 and 13.

$$i_1 = i_o x - i \quad (12)$$

$$i_1 = i_o x - \frac{i_o L}{\sinh(aL)} \sinh(ax) \quad (13)$$

*Formula for using boundary conditions for grounded system:* at the beginning of the line  $x = 0$  and the current  $I = 0$ , whereas at  $x = L$  since the track is grounded, the leakage resistance between the track and earth is zero and the current in the tracks will be  $i_o = d_r/d_x$ . Thus, the leakage current up to any point  $x$  can be calculated by using Equations 14 and 15.

$$i_1 = i_o x - i \quad (14)$$

$$i_1 = i_o x - \frac{i_o \sinh(ax)}{a \cosh(aL)} \quad (15)$$

where, in Equations 10 through 15,

$i_o$  = originating current per unit length of line assumed uniformly distributed,

$i$  = total current in rails at any point distant  $x$  from the outer end of the line,

- $e$  = potential difference between tracks and ground at any point distance  $x$  from the end of line,
- $i_1$  = total leakage current up to any point,
- $r$  = leakage resistance between tracks and remote earth per unit length of line,
- $\delta$  = resistance of track per unit length of line,
- $x$  = distance from outer end of line of any point under consideration, and
- $L$  = total length of line.

Making use of the above equations, Figure 8 defines the stray current curves. These curves show the effect of feeding distance on stray current for a defined load of 40 amperes per 1,000 feet, length of line 20,000 feet, leakage resistance of  $0.4 \Omega$  for 1,000 feet of double track, and track resistance of  $0.004 \Omega$  per 1,000 feet. Figure 8 allows a 10% increase in the resistivity of the track to account for cross bonding. The figure depicts the total current at any point on the line, stray current for a grounded and ungrounded bus with station at the end of the line, and then for an ungrounded bus with a station in the middle of the line reducing the feeding distance by half. It is observed that by providing the supply station at the middle of the line instead of at the end, the maximum value of the stray current can be reduced from 147 to 24 amperes (1).

Equation 16 shows the maximum stray current for an ungrounded system.

$$i_1(\max) = \frac{i_0 L}{aL} \left[ \cosh^{-1} u - \frac{1}{u} \sqrt{u^2 - 1} \right] \tag{16}$$

where  $u = \frac{\sinh(aL)}{aL}$

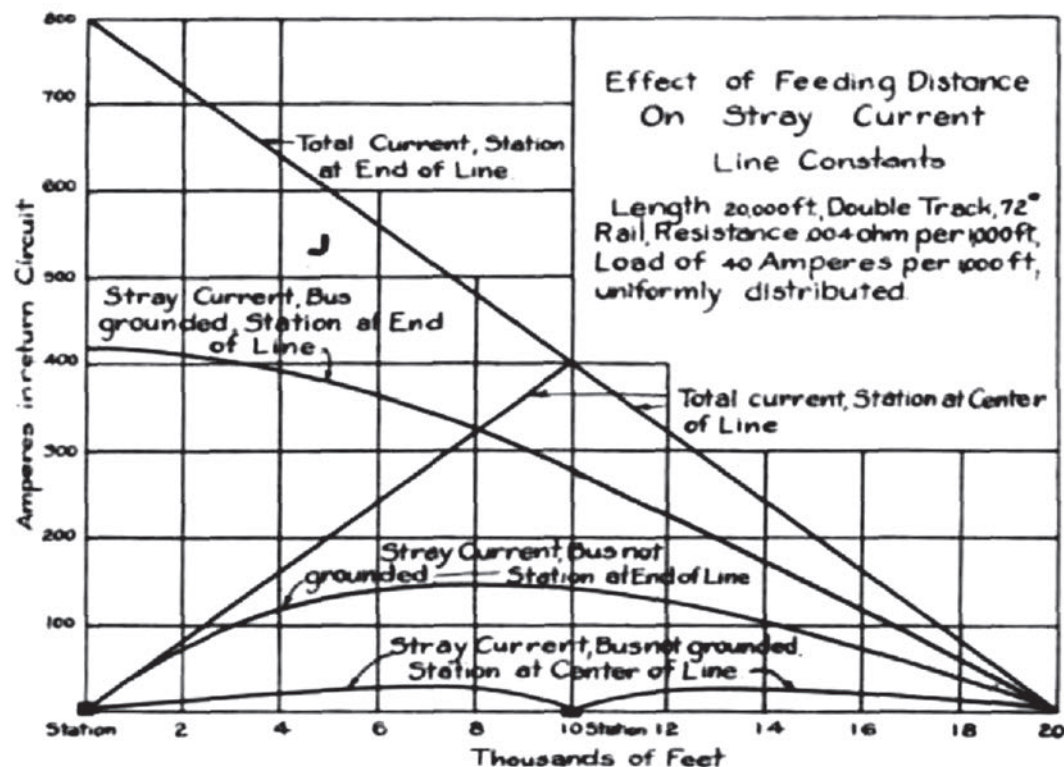


Figure 8. Effect of substation spacing on stray current (1).

Equation 17 shows the maximum stray current for a grounded system.

$$i_1(\max) = i_o L \left( 1 - \frac{\tanh(\nu)}{\nu} \right) \tag{17}$$

where  $\nu = aL$

Potential gradient on the tracks and potential difference between earth and rails can be calculated by using the preceding equations.

The potential gradient and potential drop (respectively) for an ungrounded system are presented in Equations 18 and 19.

$$E_1 = \frac{i_o L \delta \sinh(ax)}{\sinh(aL)} \tag{18}$$

$$E_1 = \frac{i_o L \delta}{a \sinh(aL)} [\cosh(aL) - 1] \tag{19}$$

The potential gradient and potential drop (respectively) for a grounded system are presented in Equations 20 and 21.

$$E_2 = \frac{i_o \delta \sinh(ax)}{a \cosh(aL)} \tag{20}$$

$$E_2 = \frac{i_o \delta}{\cosh(aL)} [\cosh(aL) - 1] \tag{21}$$

Figure 9 shows the overall voltage curves for the same line when the station is at the end, in the middle of the line (two stations), and at one third and three fourths of the total distance (three stations). The curves shown are based on a theoretical condition with no stray current

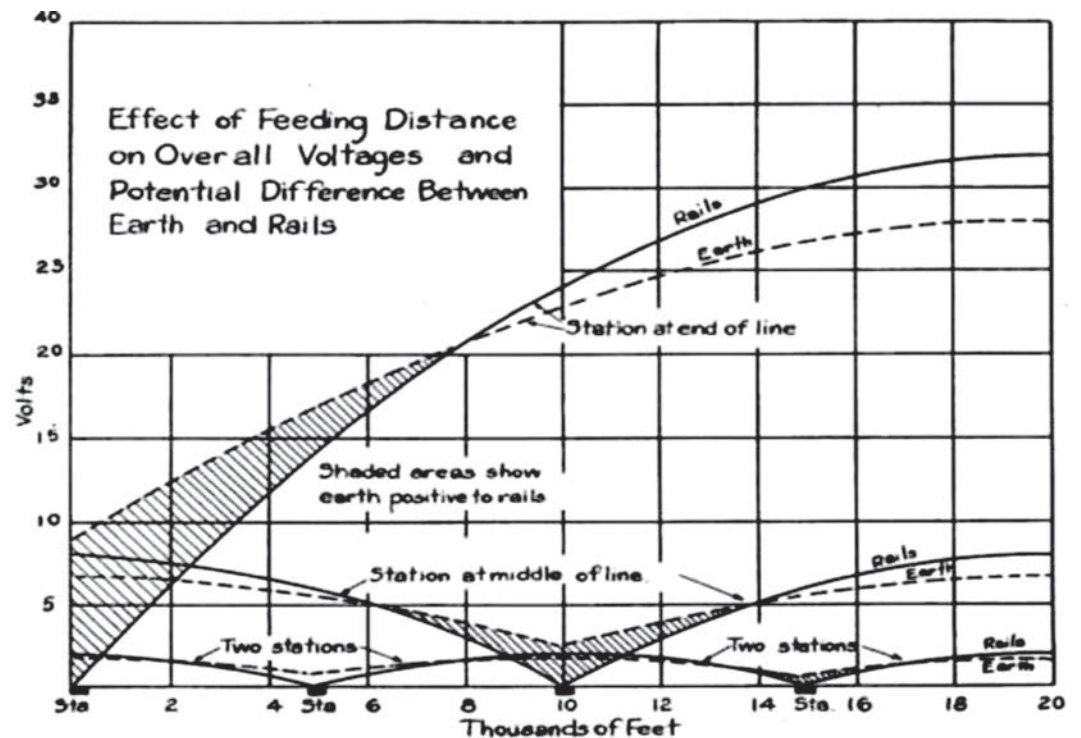


Figure 9. Effect of substation spacing on voltage (1).

whereas the actual curves will be less since a portion of the current will leak to the earth (1). The electrolysis committees observed that the overall voltage reduces by the square of the feeding distance when the feeding distance is shortened (see Figure 9). Considering this marked effect on the reduction of the stray currents and overall potentials due to the reduction in the feeding distance, further detailed studies were conducted in the United States. The initiation of automatic and semiautomatic controls for substations made it economically feasible to increase the number of feeding points.

**Three-wire traction power system and other methods.** This method was similar to the city power system, in which one trolley is negative and the other trolley is positive, and the tracks act as a neutral conductor. With proper application, this method not only reduced the stray current to one-half the value on some existing transit systems but also gave a better operating voltage for the cars (1). This method required the third and fourth rail to be a positive feed and negative return, respectively. However, because of the cost implications of adding a fourth rail or running two trolley poles in parallel on a single car, most transit agencies did not adopt this method.

Besides the adoption of the aforementioned mitigation methods to control the leakage of stray current, further mitigation methods were warranted and thus procedures were adopted to protect the utility structures near the transit system that could be damaged by stray currents. These measures included surface coating of pipes, use of conduits in cable construction, use of insulating joints, pipe drainage, and interconnection of affected structures and the rail return circuit. Other measures included keeping new utility construction at a greater distance from rail lines, avoiding the crossing of rail lines, and placing utilities as deep as possible where the utilities must cross the tracks.

Some of the methods proved effective, and some of the methods required more testing and development and were thus studied and investigated further. As with any other mitigation method, however, these procedures had limitations. While some methods that were originally recommended by the corrosion committee in 1921 are in use, the drainage bond mitigation technique was widely criticized later by the engineering community due to the variation of the conductivity of different types of pipes under different conditions, their material properties, and variety of joint types.

Drainage bonds allow stray current to drain from underground structures through the switch back to the negative bus but prevent current flow in the opposite direction. A key fact to remember is that this use of diodes is different from diode grounding. In drainage, bond diodes and reverse switches are used to mitigate stray current corrosion on an affected structure. Insulated wires or cables are run from underground pipes or metallic structures to transfer and conduct the current from such structures to the substation (32), thus, potentially reducing the flow of current from such structures to earth and other conductors. Three types of drainage bonds in use are the following.

*Direct drainage bond:* as the name suggests, it is a direct bond between the affected structure and the substation (or return circuit) and may include resistors. In a direct drainage bond, the current may flow in both directions. Therefore, direct drainage bonds may be used only when the potential at the connecting point of the bond to the DC current source is always more negative than the potential of the interfered structure, that is, the direction of current flowing in the bond will never reverse.

*Forced drainage bond:* forced drainage bond includes a separate source of DC power to enhance the transfer of the stray current. Generally, forced drainage bond (also known as forced electric drainage) is used when a direct or unidirectional drainage insufficiently drains

all stray currents from the affected structure, because the interfering structure does not have a sufficiently negative potential. The technique is used where the stray current originates from a DC traction system.

For large and frequent voltage variations between the running rails and the interfered structure, the drainage current and the potential of the structure will vary considerably. The potential of the affected structure can be maintained more negative than a preset value by the use of an automatically controlled forced drainage bond. When using this technique, the selection of a suitable site for the permanent sensing electrode must be done carefully.

*Unidirectional drainage bond:* unidirectional drainage bond will include a diode to ensure that the current flows in one direction only. Therefore, the unidirectional drainage bonds may be used where the potential of the interfered structure is not always more positive than the potential of the DC source, for example, DC traction systems.

Accurate design of drainage bonds is essential where excessive drainage might compound the problem and inadequate drainage might permit corrosion to continue. Even though drainage bonds are not popular, research shows they are still used by some transit agencies to avoid unsafe levels of track-to-earth voltages caused by stray current.

### *1960s to 1990s*

Taking advantage of the studies and detailed investigations conducted in the earlier era, most transit agencies adopted recommendations back then and augmented some of the mitigation methods with the latest technological advances to further reduce the stray current to tolerable levels (once detected). More advancements were made in the areas of track-to-earth resistance, rail return circuit resistance, TPS distance, conductance of negative conductors, modification of surrounding underground utilities, location of track cross bonds, and magnitude of propulsion current.

Design solutions, including the use of nonmetallic pipes for new utility lines, making metallic pipelines electrically continuous, installation of testing locations along new track construction, and maintenance solutions, were jointly recommended by rail transit agencies and utility companies.

Significant adjustments were made to some rail transit systems, new and old alike, to keep the stray current leakage in check by decreasing the rail return circuit resistance and increasing the resistance of the rail-to-earth leakage path (3). Decreasing the resistance of the rail return path was achieved by

- Increasing the cross-sectional area or size of the rail, which is achieved by using standard size rails ranging from 90 to 120 pounds (115 RE tee is the commonly used rail with a longitudinal resistance of around 40–80 m $\Omega$ /km).
- Maintaining a continuous electrical path for the negative current by using continuously welded rails and welded cable bonds on special track work and frequent cross bonding (every 500 to 1,000 feet).
- Decreasing the TPS spacing to 1 to 2 miles to reduce the voltage drop between the two substations.

Increasing the resistance of the rail-to-earth leakage path, which is considered the most useful approach to mitigate the stray current leakage, was accomplished by undertaking the following measures (3):

- Increasing the rail-to-earth distance by using well-graded, well-drained, and clean ballast, insulated track fasteners, and sealing compound or rail boot.

- Maintaining an ungrounded or diode-grounded negative circuit, though some researchers have observed that the rail life on diode-grounded transit system reduces to 20% of the normal life (10).
- Isolating the track in yards and storage areas from the main track (33).

For the safety of the agency staff from electrical shock in yards and shops, running rails were directly grounded and earthed back to the nearest substation via insulated cables. This resulted in excess leakage of stray current, since the only way back for the current to the substation was through the ground that contributed to the current leakage. Suggestions were made to provide a dedicated substation for the yard tracks and isolate them from the main-line tracks.

Though some of the mitigation methods established in this era could be applied only to new transit systems (like grounding system, TPS spacing, or rail cross section), other mitigation methods could be applied to both old and new systems. Suggestions were made for a regular inspection, testing, and maintenance program following severe weather changes, street and pavement repairs, and after track and substation repair work to minimize the slippage of stray current leaks and avoid hefty cost repercussions in the form of utility line corrosions. Figures 10, 11, and 12 represent an example of a poorly insulated fastener connection, broken rubber boot, and a missing insulated fastener clip and a rubber boot sleeve, respectively. Such careless mistakes can happen during construction, installation, and operation and were noticed during the stray corrosion testing conducted on tracks under construction. This is an example of a correct approach but of failed installation and maintenance, leading to stray current leakage.

### *2000s to the Present*

Design of earthing installations, TPS spacing, track-to-earth resistance, and return circuits for DC transit system are the most important defensive methods for controlling stray current and touch potentials. Most newer rail transit agencies have learned from past experiences and have started designing their rail lines with provisions for the control of stray current within the limits of their transit system by increasing the track-to-earth resistance. In the process, a few transit agencies have also incorporated testing and maintenance plans in their design criteria document. Tests like pipe-to-soil potential, track-to-earth resistance, track slab current measurements, and



**Figure 10.** *Cracked insulation cap on the fastener clip.*



**Figure 11.** Broken rubber boot on the rail requiring excavation.

cell-to-cell potential measurements are recommended by some transit agencies in their design criteria manuals.

Various isolation techniques have been implemented by DC-powered rail transit agencies for the control of track-to-earth resistance in embedded tracks. This includes the use of rail boot. In the last two decades, the practice of rail boot usage has seen a significant increase by transit agencies in the United States for controlling the leakage of current in embedded track sections. However, experience has shown that the rail boot alone cannot always control the stray current leakage and that it is important to supplement the rail boot with additional stray current collection and mitigation techniques. These methods reduce stray current corrosion by using various combinations of mitigation and collection techniques including, but not limited to, using elastomeric grout, insulating rail fasteners, embedding rail in troughs, providing current collection mats, and using collector cables.



**Figure 12.** Missing insulation at clips and missing rail boot overlap.

**Table 5. Stray current mitigation methods used for corrosion control.**

Description	Corrosion Committee 1921	Currently Used
Decreasing the Resistance of the Rail Return Path		
Rail size (cross-section area)	X	X
Rail bonds	X	X
Cross bonding	X	X
Parallel conductors	X	X (rarely)
Traction power substation	X	X
Drainage bonds (case-by-case basis)	X	X (rarely)
Increasing the Resistance of the Earth-to-Rail Leakage Path		
Track-to-earth resistance	X	X
Ungrounded traction power substation	X	X
Storage yard/main-line isolation	X	X

It is also evident that most of the mitigation methods and principles suggested by the corrosion committee that originated from the 1920s are still in use. Technical advancements have been made in mitigation methods, and new methods have been embraced by newer rail transit systems. However, the decision of when to use the relevant applicable method or a combination of methods and what level of stray current corrosion protection is needed still remains ambiguous for some rail transit providers. Despite recent technology advancements, the dynamic nature of the stray current problem renders it challenging to control it to a manageable level. Research has been conducted with innovative and experimental approaches like forcing the return current to return through a return conductor wire instead of rail or earth (34). However, the proposed return circuit decreases system efficiency. Moreover, transit agencies have started adding their own test facilities for the collection of stray current data in addition to utility company test facilities.

Table 5 lists some critical stray control measures and principles identified in 1921 by the corrosion committee and still being used in present design supplemented by some advancement and recent developments.

Following are various other methods or techniques that are used stand-alone or in combination with each other to achieve SCC (17):

- Floating, diode earthed, and solidly earthed schemes;
- Grounded systems and substations;
- Floating returned rails;
- Insulating pads and clips;
- Insulating direct fixation fasteners;
- Minimizing the stray current leakage path through rail or ballast contact by maintaining the ballast at a minimum of 1 in. below the bottom of the rails;
- Cross bonding between rails and between tracks to maintain equal potentials of all rails;
- Bonding rail jumpers at mechanical rail connections for special track work;
- Insulating switch machines at the switch rods;
- Utilizing separate traction power substations for the main line, yard, and shop;
- Insulating the impedance bond tap connections from the housing case;
- Maintaining as close substation spacing as practicable and as cost effective;
- Placing substations near points of maximum train acceleration;
- Increasing system nominal voltages;
- Maintaining electrical continuity in tunnel liners and reinforcing steel;
- Cathodic protection (CP);
- Use of rail boots or insulating membrane for embedded rails;

- Use of high resistivity concrete mix (chloride free) (18);
- Epoxy coated reinforcement (not common) (35);
- Use of current collection mat and collector cable (36);
- Conducting regular testing of the transit system and nearby utilities; and
- Maintaining an ongoing maintenance program that monitors rail-to-earth resistance values and keeps track-bed areas clean and well drained.

While not all the methods can be implemented for every transit system, the research thus far has indicated that most of the design parameters like traction power, utility coatings, CP, substation spacing, and train headways for the transit system are standardized with the exception of track-to-earth resistance. Cathodic protection has been a popular and the most utilized mitigation technique to address both galvanic and stray current corrosion by the utility companies.

Research has been carried out on the resistivity of concrete in the presence of stray current. The research covers the corrosion behavior of steel and steel fibers in concrete (18), corrosion damage of steel in concrete (37), and the corrosion rate of steel in concrete (38) in the presence of stray current. It is beyond the scope of this guidebook to go into detailed analysis of the resistivity of concrete and corrosion of steel in concrete. It is prudent, however, to share the findings of research that show that stray currents induce corrosion in steel in the presence of chlorides (39) whereas the risk of corrosion on steel fibers is low, primarily because the electrical connection between the steel fibers (manufactured fibers composed of stainless steel) is unlikely for the volume ratio of steel fibers (40).

Research also shows that stray currents may aggravate fatigue damage of reinforced concrete (41). Moreover, it was observed during the construction of a local DC street car project that high resistivity concrete presents construction challenges. Challenges included special efforts for finishing, early-on shrinkage cracking of concrete, and extended curing times (42).

A study by Yang et al. showed that stray current corrosion resistance of high resistive concrete with fly ash and powdered slag is more than five times that of regular concrete with 100-year-of-concrete design service life (43).

## 2.8 Rail Sections and Rail Boot

There are two different applications for the tee rail (Figures 13 and 14). In one application the flangeway is constructed of grooved concrete and the other application includes the rubber boot to snap on to the flangeway section (creating a grooved section). The second application, which is the preferred one, addresses the problem of dirt and debris being collected in the concrete flangeway because dirt and debris provide a conductive route for stray current. The rail boot snug fits both the girder rail and the tee rail and comes on a reel that is easy to deliver on the site along with other secondary joining materials. Depending on the boot manufacturer, the secondary materials may include epoxy grout, plastic ties, sealant to bond the rubber boot with the boot sleeve, duct tape, and the boot sleeve to connect and overlap two rubber boots at each end (44).

Research has shown that the rail boot provides perfect insulation when first installed but with time, due to being in constant contact with the road traffic, different weather variations, standing water, and rail traffic, it inevitably undergoes wear and tear and thus allows stray current to find a path to leak through it. Such current leakages are common in regions with moderate-to-heavy rainfall and in busy urban streets. Therefore, drainage design and track maintenance play a major role in achieving and maintaining SCC.



**Figure 13.** Tee rail with grooved rail boot.

Special attention is also warranted for the proper placing of the rail boot and the subsequent concrete pour around it during construction. When the proper placing of the rail boot and the subsequent concrete pour around it during construction had not been done meticulously, there were instances where the track failed the safety test and the boot had to be reinstalled. Examples of such failure were observed during site visits to both local and international transit agencies, where multiple sections of track were dug up to reinstall the boot and clips. The damage to the rail boot results in degradation of the track-to-earth resistance and therefore is responsible for increased stray current leakage in a transit system.

## 2.9 Design Criteria and Standards

A review of the design criteria or manuals of a sample of DC-powered transit agencies listed in Table 6 was completed to understand the source and origin of the limiting values listed in these documents and the isolation techniques adopted by agencies. However, none of the documents



**Figure 14.** Tee rail with rail boot and concrete groove.

**Table 6. Design criteria manuals for transit agencies.**

Reference	Transit Agency	Title	Latest Revision
45	Houston METRO	<i>Design Criteria Manual</i>	April 2007
46	Phoenix METRO	<i>Design Criteria Manual</i>	January 2007
47	Denver RTD	<i>Design Guidelines &amp; Criteria</i>	November 2005
48	New York City Transit Authority	<i>Corrosion Control Manual</i>	June 1984
49	Seattle Sound Transit	<i>Link Design Criteria Manual</i>	May 2011
50	Utah Transit Agency	<i>Design Criteria Manual</i>	July 2010
51	Portland, Oregon	<i>TriMet Design Criteria Manual</i>	January 2012
52	Washington, DC	<i>Streetcar Design Criteria Manual</i>	January 2012

mentioned the origin or the basis of the limiting values for the return voltage or the stray current. In some cases, it was not clear if the transit agencies conducted any initial baseline surveys to come up with these limiting values. These documents were either downloaded directly from the websites of the transit agencies or were provided by the traction or corrosion department at the agency. Some transit agencies did not have the design criteria document or elected not to provide any agency document.

There is an American Society of Testing and Materials (ASTM) designation G165-99 that was issued in 1999 as a standard practice for determining rail-to-earth resistance. The authors found that some transit agencies or providers did not follow this practice.

The authors reviewed the following English versions of European and Australian standards to understand what international transit agencies are using for SCC:

- BS EN 50162:2004, British Standards Institution (BSI), Protection against corrosion by stray current from direct current systems, issued in 2004.
- BS EN 50122-1:2011+A2-2016, BSI, Railway applications—Fixed installations—Electrical safety, earthing and the return circuit. Part 1: Protective provisions against electric shock. This standard issued in 2016 specifies the protective provisions in fixed installations related to electrical safety in AC and DC traction systems.
- BS EN 50122-2:2010, BSI, Railway applications—Fixed installations—Electrical safety, earthing and the return circuit. Part 2: Provisions against the effects of stray currents caused by DC traction systems. This standard issued in 2010 explicitly deals with stray currents resulting from DC traction power and is the most applicable standard to this research.
- BS 7430:2011, BSI, Code of Practice for Protective Earthing of Electrical Installations. This standard issued in 2011 gives guidance on the methods that may be adopted to earth an electrical system to limit the potential.
- EP 12 30 00 01 SP, Electrolysis from Stray DC Current, RailCorp Engineering Standard—Electrical, Version 3.0, issued in 2012.
- SPG 0709, Traction Return, Track Circuits and Bonding, RailCorp Engineering Standard—Electrical, Version 2.5, issued in 2011.
- APTA RT-S-FS-005-03, Standard for Traction Electrification Stray Current Corrosion Control Equipment Inspection and Maintenance, 2004 draft.
- NACE International, Task Group 297, Direct Current Operated Rail Transit Stray Current Mitigation, <https://www.nace.org>.

The previous eight standards specify appropriate SCC measures that can be applied to DC systems along with some defense strategies against the effects of stray currents. However, these standards do not specify SCC testing or quality control methods.

## 2.10 Chapter Summary

With light rail transit (LRT) systems typically operating on embedded tracks in city streets, stray current corrosion is a major concern for track, utility, and other infrastructure owners near the DC-powered transit system. The literature review has shown that various mitigation measures and collection techniques are in use by transit providers. The literature review has also highlighted that based on site conditions, a floating system with ungrounded substations, shorter TPS spacing, and high track-to-earth resistance are the key design mitigation measures on newer systems.

The stray current collection system is suitable for systems where the level of stray current produced by the transit system cannot be completely controlled by rail insulation. An exception would be where stray current leakage is high. The goal of insulating the rail is to control the current at the source and minimize the stray current leakage. This “control at source” is achieved by reducing the distance between the TPSs, maintaining a continuous electrical path, using better coatings, cross bonding, and insulating track fasteners. The control at the source is also achievable via the use of rail boots, coating and insulating rail troughs, and isolating the tracks in yards and storages. However, research also has shown that there will be a certain amount of stray current leakage despite these control measures. This leakage usually happens after a few years of track life or even earlier if the tracks are not routinely maintained and tested.

Stray current leakage cannot be completely eradicated, but it can be kept within acceptable levels and some of the newer transit agencies have been successful in achieving the desired levels of stray current. Many agencies, however, still struggle to control stray current corrosion. This situation may be improved through development and adoption of national standardized guidelines, principles, and testing procedures and through developing and implementing regular testing and maintenance plans at the system level.



## CHAPTER 3

# Stray Current Control Design, Mitigation, and Testing of DC Rail Transit Systems

Stray current leakage and the corrosion caused by this leaked current in DC traction power systems have combined to be an ongoing issue especially in slab or embedded tracks. These tracks typically run through urban traffic areas, city centers, tunnels, and between utility lines. Their location requires the rail to be continuously isolated to provide adequate track-to-earth resistance. Ballasted and direct fixation tracks provide much better track-to-earth resistance when equipped with isolation pads under the rail and exhibit higher stray current protection. The transit agencies surveyed during the research for this guidebook are cognizant of this issue and of the benefit of defining the limiting values for track-to-earth resistance versus current leakage. However, in the absence of defined guidelines and initial soil investigations, it is hard to maintain the tracks and define the limiting values relevant to the local conditions.

### 3.1 Transit Agency Surveys

An initial desk study of numerous DC-powered transit systems was carried out to understand the standard practices adopted for the control of stray current by these transit agencies. The data collected included information on design criteria, performance specifications, constructability issues, and physical environment. Based on the findings of the literature review and the list of transit agencies provided by TCRP (and through personal contacts of the lead investigators), a mix of 30 transit agencies (21 national and 9 international) were contacted. Data and information on existing stray current mitigation and collection procedures, methods of stray current testing and measurement, criteria for acceptable levels including rail-to-earth resistance, and agency specific criteria was collected to understand existing or previous issues. Table 7 provides the list of national and international agencies that participated by responding either to one of the questionnaires or by agreeing to a telephone interview.

Appendix A presents the introductory questionnaire (short questionnaire) that was e-mailed to the national and international transit agencies listed in Table 7. The questionnaire was formatted to get to the premise of the limited stray corrosion criteria and guidelines used by these transit agencies. Though most of the transit agencies requested anonymity, a few agencies completed the questionnaire under conditions of complete anonymity. Therefore, their names are not listed in Table 7. Appendix B provides a matrix listing the responses received from some of these transit agencies, with responses to the questionnaire based on the survey results between 2012 and 2014. The answers provided by the transit agencies have not been vetted with the actual data, design, or configuration of their transit systems.

Following is a synopsis of the key findings and responses gathered from short questionnaires and from face-to-face interviews with the transit agencies or their consultants.

- Fifty percent (50%) of the transit agencies or their consultants reported being aware of a stray current corrosion issue at their system. Sixteen percent (16%) of the remaining responded

**Table 7. Transit agencies that responded to the questionnaire.**

Transit Agency Name and Geographic Location	
MTA Maryland, Baltimore	New Jersey Transit, Newark
BART, Oakland, CA	RTA, New Orleans, LA
Charlotte Area Transit System, NC	New York City Transit
CTA, Chicago, IL	SEPTA, Philadelphia, PA
City of Calgary, Canada	Valley Metro, Phoenix, AZ
Copenhagen Metro, Denmark	TriMet, Portland, OR
RTD, Denver, CO	Public Transport Victoria, Australia
Edmonton Transit System, Canada	Rio Metro Concession, Brazil
GCRTA, Greater Cleveland, OH	Sacramento Regional Transit, CA
METRO, Houston, TX	UTA, Salt Lake City
LA METRO, Los Angeles, CA	Sound Transit, Seattle, WA
Manchester MetroLink, United Kingdom	Toronto Transit Commission, Canada
MTA Maryland, Baltimore	Via Quatro Line 4, Sao Paulo, Brazil
MBTA, Boston, MA	WMATA METRO, Washington, D.C.
Metro Transit, Minneapolis, MN	Yarra Trams, Victoria, Australia

that they were not aware of any stray current corrosion issues at their system. The rest did not respond to this query.

- One hundred percent (100%) of the transit agencies responded to the question on substation spacing. Eighty percent (80%) indicated that the spacing between most of the TPSs was <1 mile. However, there are few sections where the distance ranged from >1 mile to <2 miles, which is a preferred SCC measure.
- Eighty percent (80%) of the transit agencies responded *Yes* to the question on having conducted the baseline survey, with roughly 30% acknowledging the fact that the survey was only conducted on some of the newer lines.
- All U.S. transit agencies, with the exception of one transit agency, responded to the question on limiting values for rail-to-earth resistance maintained on their tracks. Following is the breakdown of their responses:
  - Twenty-three percent (23%) maintain 250  $\Omega$ /1,000 track feet;
  - Fifty-four (54%) maintain 500  $\Omega$ /1,000 track feet; and
  - Fifteen percent (15%) maintain 1,000  $\Omega$ /1,000 track feet.

The remaining U.S. transit agencies either did not respond to this question or stated that it was maintained lower than 100  $\Omega$ /1,000 ft.

Compared with this, 50% of the international transit agencies responded that they follow the BS EN 50122-2:2010 and the remaining international agencies either did not respond or presented numbers ranging from 5  $\Omega$ /1,000 track feet to 250  $\Omega$ /1,000 track feet. The rail-to-earth resistance is a critical parameter as it is one of the first lines of defense against stray current leakage.

This short questionnaire served as a first blush analysis on the pulse of the industry, as the industry views itself, related to the current practice on stray current corrosion, mitigation, and testing. In general, the data sample collected as part of the short questionnaire served the purpose of an initial analysis and warranted the development of a more detailed questionnaire (long questionnaire).

Based on the willingness of transit agencies to participate in a more detailed questionnaire and to advance the survey of the transit agency stray current corrosion data, a long questionnaire with 51 questions was e-mailed to the transit agencies. Eighty-five (85%) of agencies had initially agreed to contribute to this long questionnaire; 35% of them actually responded.

Out of the 35%, some of the agencies completed the questionnaire with a request for anonymity. Appendix C presents the long questionnaire.

Appendix D presents a matrix listing the summary of the agency response findings. Following is a synopsis of the key findings and responses gathered from long questionnaires and face-to-face interviews with the transit agencies or their consultants.

- All but one of the transit agencies answered the question on the type, size, and cross section of the rail. The rail cross section is an important design parameter for the control of stray current as it defines the rail resistivity, the concept and relevance of which are elaborated in the literature research chapter.
- One hundred percent (100%) of the transit agencies responded to the question on TPS spacing. This longer questionnaire included a query about the largest spacing between two TPSs. Most of the transit agencies stated that the largest spacing between two TPSs was < 2 miles, which is a preferred SCC measure.
- In response to the question on guidelines followed for the control of stray current leakage and mitigation design, most of the U.S. transit agencies mentioned that they have their own design criteria. They elaborated that these criteria define the limiting values for track-to-earth resistance and stray current testing and maintenance procedures, which helps them in maintaining the stray current leakage. Conversely, 100% of the international transit agencies referred to the BS-EN standards developed for the stray current leakage.
- Thirty-three percent (33%) of the U.S. transit agencies stated that they measure the track-to-earth resistance as part of their regular testing. These agencies have local design criteria manuals that define the limiting values and warrant testing and maintenance plans. However, the absence of regular testing to ascertain if recommended values in design criteria manuals are maintained indicates the need for better understanding and implementation of the guidelines proposed in those manuals.
- Ninety-nine percent (99%) of the transit agencies acknowledged that they either have stray current issues or have encountered them in the past. Most of the agencies also mentioned that in the absence of regular testing they usually find out about the stray current problems when a utility or third party complains about their pipes getting affected by the stray current leakage.
- With the exception of one international transit agency, none of the transit agencies shared their historical data on stray current leakage and corresponding mitigation measures. The agency that provided data requested to keep it confidential.
- Most of the U.S. transit agencies agreed that they would like to see a national guidebook for stray current design and mitigation measures for DC-powered rail. They emphasized the fact that a step-by-step guide for mitigation and then maintenance and testing will help the transit agency in keeping stray current leakage in check.
- A few of the agencies shared information on the cost of mitigating or repairing track due to stray current issues.

**Table 8. Corrosion consultants interviewed.**

Corrosion Consultants
Corpro (International)
UTRS (now with STV)
V&A Engineering
LTK
Parsons (International)
Intertek (International)

### 3.2 Transit Agency and Corrosion Consultant Interviews

During the coordination process for the questionnaires, it was concluded that some of the transit agency employees either are not properly trained or knowledgeable on the specifics of the corrosion mitigation for their system or were reluctant to release the information. In some cases, the questions were left either unanswered or delegated to their corrosion consultants. A supplemental interview of a cross section of corrosion consultants was warranted to get a viewpoint based on their experiences with some of these agencies. Table 8 highlights the list of corrosion consultant experts that participated in the interview process.

The feedback from general consultants indicated the need for experienced consultants for stray current testing and control or for focusing on getting the transit agency staff more trained and comfortable with carrying out stray current measurements. The consultants also unanimously agreed that there is a dire need for a guideline to address the design, testing, and maintenance of the stray current control process.

Many of the agencies did not want to share transit agency specific data and requested anonymity. But the previous data collection exercise, through questionnaires and interviews, not only helped in understanding the physical and environmental settings of the transit systems but also provided an insight into the many means and methods used by the transit agencies to mitigate and collect stray current leakage.

Judging from studying the responses to both of the questionnaires and interviews with transit agency personnel and corrosion consultants, the critical needs of the industry follow:

- Implementation of improved rail insulation (track-to-earth) techniques;
- Guidelines for acceptable SCC;
- Ongoing track maintenance program (keeping rail track-bed areas clean and drained);
- Proper placement of a TPS along the track using traction power and stray current corrosion modeling;
- Standardization of a regular testing program for transit agencies; and
- Standard testing methods for stray current and their limiting measurements (based on baseline survey).

### **3.3 Transit Agency Essentials and Corrosion Issues (Case Studies)**

A decision tree, presented in Appendix E, was developed to narrow a select list of transit agencies for further detailed analysis and presentation. Four representative DC-powered rail transit systems were shortlisted for case studies to evaluate effective practices for SCC and control of track-to-earth/rail-to-earth voltages. To ascertain that the data collected from these agencies was a true cross-sectional representative of the industry, this sample set included (a) an agency with relatively newly constructed tracks, (b) an old agency, (c) an agency with tracks under construction [both LRT and heavy rail transit (HRT)], and (d) an international transit agency with overhead contact systems.

Subsequent sections describe a summary of the case studies on these four agencies. Face-to-face interviews and site visits were conducted between 2012 and 2014. The transit agencies may have expanded their system, changed their system configuration, or updated their stray current collection and mitigation techniques. Names of transit agencies are anonymous at the request of transit agency personnel. This information has been gathered not only from in-person interviews and site visits but also by collecting live testing and maintenance track data.

#### **3.3.1 Transit Agency 1**

Transit Agency 1 comprises approximately 13 miles of LRT and is powered by 750 volts DC via an overhead catenary system (OCS). This includes the recently opened extension along one of the routes. The LRT runs through the urban shared and dedicated right-of-way (ROW) with embedded, direct fixation track, and ballasted track sections. The TPSs are spaced at not more than 1 mile apart (with an exception of one location where the distance is close to 1½ miles). The negative return system is through the running rails. A shop and yard facility is electrically isolated from the mainline system. At the time of the interview, the extension line was not in revenue service so the interview focused on the issues on the existing line.

The track is mostly embedded (95%) with an approximately 1-mile-long direct fixation track and a small section of ballasted track. The transit system uses 115 RE rail (i.e., a certain rail section, 25 rail) on most tracks, with rail boot system and flangeway filler for the embedded section and concrete ties with insulated rail clips for the ballasted section to control the stray current leakage. Additionally, it uses continuously welded rails, direct fixation fasteners, cross bonding, tie and ballast at-grade track, and a continuous reinforcing steel mat with bonding cables in the concrete section to provide electrical continuity. This steel mat collects the stray current escaping the rails and conducts it along the track to the point where it reenters the running rails. This mat not only assures structural continuity that brings back the current to the return path but also controls the stray current from taking any unwanted routes, eventually sparing the surrounding utilities and infrastructure from corrosion. Test stations are provided at approximately 300-foot (on newer track) to 500-foot intervals to provide measurements of track-to-earth resistance.

At gaps around bathtubs, at concrete paver locations, and around special track work, FX-120 polymer fills in the gaps. The injection of silicon material along rubber boot interfaces increases the track-to-earth resistance in those areas. All items that connect to the running rails (e.g., switch heaters, signaling system, and rail lubricators) and to the negative buses within the substation are suitably insulated, ensuring that there is no link between the grounding structures and the negative return.

An important element of the SCC for the transit agency is the liaison with the utility owners that have utilities near the tracks. Numerous utilities exist along the ROW, including some major lines like gas lines and municipal water pipelines. In addition to the stray current design provided by transit agency, the local utility owners near the tracks conduct testing on their pipelines and maintain their own sophisticated CP systems to protect their infrastructure.

The preferred rail-to-earth resistance of the embedded track is 100  $\Omega$ /1,000 feet of track and the conservative contract requirement is 250  $\Omega$ /1,000 feet of track. The corrosion consultant established these resistances after conducting the rail-to-earth testing of the tracks using ASTM standards. Figure 15 shows the rail boot installation on the rail on a section of the tracks under construction, and Figure 16 shows the section of the rail that sits on reinforced concrete slab, which also has a steel mat for corrosion control. The transit agency has established a track maintenance and inspection plan based on the design criteria manual, which includes



**Figure 15.** Section of flangeway filler rail boot during construction.



**Figure 16.** *Steel reinforcement for the embedded slab track.*

both LRT and bus rapid transit systems and a dedicated chapter on corrosion control comprising stray current corrosion. The transit agency carries out systemwide stray current testing such as track-to-earth resistance, track slab stray current flow, and audio frequency tracing measurements, if needed.

### **Testing Methods**

The following tests are conducted as part of the overall track stray current testing and maintenance:

- Visual inspections,
- Structure and/or pipe-to-soil potential measurements,
- Utility testing,
- Track slab electrical continuity and current flow,
- Bridge stray current, and
- Cell-to-cell potential gradient measurements.

The testing is conducted every 3 to 5 years based on track performance.

Figures 17 and 18 illustrate the sampling stations/process.

### **Findings from Testing and Corresponding Corrosion Issues**

Results of the testing conducted soon after the revenue service revealed that most of the track sections complied with the 100  $\Omega$ /1,000 feet of track resistance except in the following areas: rail anchors at the bridge expansion joints, track switch bathtubs, and concrete and brick pavers bridging effects at bathtubs. Most of the public utility pipes along the ROW were also tested where minor-to-negligible stray current effects were noticed. All these areas of potential concern were enhanced and from that point the transit agency now conducts testing of the track once every 3 years for the entire section and once a year along a select section of the track.

To understand the testing procedure, the need, and the method's effectiveness, ground testing was observed and performed sometimes as part of the work for this guidebook. Details of the testing and respective results were incorporated into the development of guidelines and recommendations that are presented in Chapter 4.



**Figure 17. Example 1: utility testing station.**

### *Conclusion*

When asked what the key issues are, the Transit Agency 1 staff indicated that they would rather not construct an embedded track within the urban area due to high traffic volume and regular maintenance issues. In a situation where there is no other alternate route, they would like to ensure that the rail is completely isolated (use of modified rail boot) in combination with a possible stray current collection system. This would ensure minimal-to-no leakage of current to the earth or the neighboring utilities. Moreover, as recognized in the literature review, Transit Agency 1 would like to see some guidelines and principles supporting the limiting values for stray current mitigation.

### **3.3.2 Transit Agency 2**

Since the earlier days of its service in the 1900s, Transit Agency 2 has grown to be one of the top 10 busiest subway systems in the world. Of its 840-mile-length of track, approximately



**Figure 18. Example 2: utility testing station.**

60% of the track miles are underground, with more than 470 station locations. The systems design represents three distinct styles, with the primary difference being the platform lengths. Since most of this system was built in the early to mid-1900s the system has seen a lot of upgrades. The upgrades include the one ongoing at the time of the site visit in November 2011 and then again in March 2012 involving additional tracks on the existing and new transit routes.

Transit Agency 2 is powered by 650 volts DC via the third rail with substations receiving as much as 27,000 volts from the power plants whereas the signals, station lighting, tunnel lighting, ventilation, and other miscellaneous line equipment is powered by AC. The substation spacing varies from 0.5 miles in the newer lines to not more than 1.5 miles in some of the older lines (this is after construction of some interim TPSs to reduce the spacing). The track is mostly ballasted or concrete with recently upgraded insulated clip-type fasteners for rail-to-tie connection and continuous welded sections of rail. There are still some sections with wooden ties and spikes as well; however, they are gradually being replaced (see Figure 19). The traction power system is isolated with floating negative return running rails (no grounded system by design). The rail-to-earth resistance of the track is approximately between 1 to 10  $\Omega$ /1,000 feet at its worst. Diode drains along with track bonding are used to provide SCC with cross bonding every 500 to 1,000 feet.

Transit Agency 2 does not have specific criteria or principles for the operation and maintenance of stray current corrosion and instead maintains/retains a corrosion control task force that handles the corrosion-related complaints. Thus, as stated in the literature review, the approach to address stray current issues is more reactive than proactive. A corrosion control guide was structured in 1984 that is used by the agency staff for reference and corrosion mitigation control.

### *Testing Methods*

There is no periodic inspection or testing schedule in place for Transit Agency 2. The corrosion staff is responsible for the corrosion surveys, and testing is conducted mostly to address a prevailing complaint rather than as a proactive approach. The corrosion testing crew is on duty 24 hours a day with the goal to keep the corrosion issues at a minimum. The crew has been diligently maintaining the system's stray corrosion under control (see Figure 20).



**Figure 19.** Section of ongoing construction with concrete and wooden ties.



**Figure 20.** Water pipe utility test on bridge.

### *Findings from Testing and Corresponding Corrosion Issues*

Because this system is older, issues are inevitable and they have been fixed in the past. However, the recent upgrades to the tracks and the overall system have rendered the previous corrosion records obsolete. Since Transit Agency 2 does not keep a database of existing or past corrosion issues, there are no reports generated to depict stray corrosion best management practices or documented mitigation measures that have been successfully adopted. Following are some of the issues that the agency staff mentioned that they have to address on a recurring basis:

- Water main failures or corrosions.
- Corrosion of rail spikes.
- Loss of expansion joint bonds of the elevated structures leading to corrosion of steel components.
- Failure of old lead cables.

### *Conclusion*

When asked what the key issues are, the agency staff indicated that they would like to upgrade all the tracks that are old or have not been upgraded yet, change the fastener clips, and replace the old lead cables. During the interview, they also implied that not having a source document (guideline or recommendations) for reference and standards makes their job difficult and that they would like to see a typical guideline to be followed across the industry.

### **3.3.3 Transit Agency 3**

Since its opening in the late 1990s, Transit Agency 3 has grown to become an integral part of the county's transit system. The transit agency has a combination of light rail and heavy rail and operates approximately 100 miles of LRT and HRT, with more than 100 station locations. The heavy rail lines share the ROW for a short length of the route whereas the light rail lines run on their own ROW except at grade crossings, with expected utilization of the shared ROW. The routes run in a mix of at-grade, elevated, and underground environments.

Seven hundred fifty (750) volts power the HRT system via the third rail. The LRT system is powered by 750 volts DC via the OCS with running rails providing the negative return for both

systems. The substation spacing varies from 0.5 miles to 2 miles for both the LRT and HRT systems. The track is mostly ballast with concrete ties and insulated rail fasteners. The traction power system is ungrounded with continuously welded rails, cross bonding, clip fasteners with insulation padding, and sacrificial anodes to mitigate the stray current. The design rail-to-earth resistance of the track is  $500 \Omega/1,000$  feet of rail whereas the embedded section at-grade crossings/city streets is  $300 \Omega/1,000$  feet of rail. Wooden ties and spikes are used for the tracks in shops and yards and are reasonably well isolated from the main line.

The agency does not have any track maintenance inspection plan or design criteria manual that includes guidance on stray current corrosion. The corrosion issues are managed as they arise (see Figure 21). The transit agency is currently working with a consultant to conduct the survey and testing of sections of the line and to recommend suggestions to mitigate the stray current corrosion.

### *Testing Methods*

There were no inspections or surveys conducted on Transit Agency 3 until recently. Typically, utility companies or local residents would report potential stray current issues to the transit agency staff who, in turn, would take any mitigation action as needed. However, due to the increasing corrosion issues and the expansion of the LRT system, the agency now uses the services of a corrosion consultant. The consultant conducts track-to-earth resistance and pipe-to-soil corrosion testing and provides mitigation recommendations. The same consultant is also working on preparing a detailed operations and maintenance manual, including maintenance procedures, and is providing stray current training to the transit agency staff.

### *Findings from Testing and Corresponding Corrosion Issues*

Results of the testing conducted by the Transit Agency 3 consultant reveal that the stray current corrosion activity has generally increased. Following are some of the ongoing stray current corrosion issues:

- Corrosion of the fire protection pipe system due to failure of the CP system.
- Number of other CP locations not functioning as designed.
- Corrosion of rail spikes.



**Figure 21.** Corrosion of pipes at station facility.

- Areas of low track-to-earth resistance along the lines.
- Possibility of a substation being grounded, which results in stray current leakage.

### *Conclusion*

Periodic testing and monitoring of the testing locations were identified as the key issues for the tracks. The staff at the agency indicated that they would like a consultant to keep a restricted online database of the system, including the results along with the GPS locations of the testing areas. This will provide Transit Agency 3, the consultant, and the utility owner a log of the test results along with locations. Additionally, Transit Agency 3 would like to see some more guidelines and principles to support the ongoing testing and maintenance of the tracks to avoid stray current corrosion issues.

### **3.3.4 Transit Agency 4**

The system of Transit Agency 4 comprises approximately 19 miles (32 km) of LRT/tram line powered by 750 volts DC via an OCS and a suburban rail line (rapid transit). The LRT includes the recently opened extension line (approximately 7.5 km) along one of the routes (also powered by 750 volts DC). The LRT runs through the urban shared and dedicated ROW with embedded, dual-block slab, and ballasted track sections with a total of 52 stops (stations). The TPSs are spaced at not more than 1 mile apart, with an exception of one span where the distance between the TPSs is slightly longer than 1 mile. The negative return system is through the running rails, cross bonding, and the collector cable, which is bonded to the stray current mat (wire mesh). The existing depot is divided into two areas: a storage area (yard) and a maintenance area (shop). The yard area uses the floating earth system employed on the main line, while the maintenance area is directly grounded to prevent touch potentials. The maintenance area is energized when the LRT is driven into and out of the building. At the time of the interview, another extension to the existing LRT line was under construction; however, it was not ready for revenue service.

Transit Agency 4 uses T-rail (also referred to as flat bottom) 113-pound rail with concrete ties with insulated rail clips for the ballasted section, 80-pound rail for the slab-in track section, and Corus 59R2 coated rail or Corus 35GP rail with rail boot system with flangeway filler for embedded track. Additionally, Transit Agency 4 uses continuously welded rails, direct fixation fasteners, cross bonding, tie-and-ballast at-grade track, and a steel mat stray current collector system with bonding cables in the concrete section to provide electrical continuity. This steel mat collects the stray current escaping the rails and conducts it along the track to a copper cable bonded at every 300 meters. Test stations are provided at approximately 300- to 500-foot intervals to provide measurements of track-to-earth resistance (see Figure 22).

An important element of the SCC for Transit Agency 4 is the stray current collection system and the liaison with the utility owners that have utilities near the tracks. In addition to the stray current design provided by Transit Agency 4, the local utility owners near the tracks conduct testing on their pipelines and maintain their own sophisticated CP systems to protect their infrastructure.

### *Testing Methods*

The following tests are conducted as part of the overall track stray current testing and maintenance:

- Visual inspections,
- Structure or pipe-to-soil potential measurements,
- Utility testing,



**Figure 22. Embedded and ballasted section.**

- Track slab electrical continuity and current flow, and
- Cell-to-cell potential gradient measurements.

This testing occurs every 5 years based on the track performance and current leaks.

#### *Findings from Testing and Corresponding Corrosion Issues*

There are areas of railway structure where the basic transit agency criteria for SCC has not been adequately achieved to ensure control of stray current to an acceptable level. Additionally, there is a potential risk of corrosion to third party structures such as utility pipes. In these areas, it is recommended to add measures or changes to the basic requirements. Options for these measures include fixing the epoxy coating between the rail boot and the ground in damaged areas, keeping the track clean from trash and debris, and reducing the rail potential by adding traction return cables to reduce the return circuit resistance.

To understand the testing procedure, the testing need, and the testing method's effectiveness, actual ground testing was observed and performed as part of the work for this guidebook.

#### *Conclusion*

When asked what the key issues are, Transit Agency 4 staff indicated their satisfaction with the adequacy and efficiency of the stray current corrosion levels and mitigation measures established by their consultant. With regular maintenance and testing, the stray current leakage is kept within limits described in the transit agency criteria. As for the utilities, a detailed assessment based on tests and monitoring is undertaken to assure that the stray current leakage is kept within the agency criteria.

In response to the question on standards and guidelines, Transit Agency 4 mentioned that they follow the BSI standards. However, they indicated that additional step-by-step guidance on stray current leakage, mitigation, and testing will help the agency in streamlining their stray current corrosion control process.

### **3.4 Chapter Summary**

The literature review, transit agency surveys, and case studies highlight a need for uniform design guidelines for stray current isolation and track maintenance for the U.S. DC rail transit community. Guidelines, complemented by a track maintenance and testing plan, will not only

help transit agencies in keeping the stray current leakage to a minimum but will also help in implementing QC measures. The implementation of recommendations and best management practices in these guidelines, coupled with a preplanned maintenance regime, comes with an initial cost; however, such proactive measures will help reduce the unpredictable and repetitive cost of repair and breakdown down the line.

Assessment of potential corrosion resulting from stray current should be part of the planning and design process at the inception of any project. Furthermore, testing for stray current corrosion must continue throughout revenue service. Based on interviews conducted during the course of compiling data for this guidebook, it was apparent that most of the transit agencies had not conducted prerenue testing and did not have a regular testing and maintenance plan.

It was also observed that transit agencies are not keeping a log of the corrosion issues caused by stray current or tracking the money spent to mitigate these issues. This kind of tracking would be beneficial to the rail industry in assessing the economic and logistic burden borne by the rail transit agency as a direct impact of stray current corrosion. Most of the transit agencies interviewed had at least one corrosion staff or traction power engineer on their payroll. But because of limited knowledge and understanding of stray current corrosion issues coupled with the absence of guidelines, they are forced to rely on outside consulting resources, as verified when transit agency staff forwarded the survey questionnaires to their respective consultants to complete. The DC rail transit agency staff understands that stray current corrosion is a serious issue and wants to have an amicable solution to control stray current leakage. However, they do not necessarily have the means and methods to keep the stray current leakage within limits and would like to see some defined criteria to control stray current corrosion.

Transit agency staff is also aware of the need, benefit, and importance of stray current corrosion testing, maintaining the track, and keeping it clean of debris and dirt. However, they report that due to the lack of available transit agency funds, they cannot carry out the desired testing and maintenance. A potential alternative to this lack of funding issue is that the transit agency staff could be trained on the fundamentals of stray current corrosion, track testing, and control and mitigation techniques to conduct these services in house. These measures could keep stray current levels under control and minimize the preemptive system repair costs.

# Stray Current Control Provisions for DC Transit Systems

Key decision matrices associated with implementing, maintaining, and testing of SCC and safety control of rail-to-earth potentials were developed by using the information collected from the literature review, questionnaires, data gathered during the transit agencies' and corrosion consultants' interview process, and stray current testing observations. Using these findings, proactive sequential steps are presented in the guidebook for stray current isolation and quality control. These steps include measures that need to be taken at the inception of design, at pre-construction, at construction, and at postconstruction, leading into the maintenance and testing program phase during the revenue service of the transit system. These recommendations, if followed, will assure achievement of uniform stray current isolation and quality control for a DC-powered transit system.

- *Design essentials*
  - Baseline survey,
  - Traction power model, and
  - Track design.
- *SCC*
  - Control at source and isolation techniques,
  - Mitigation, and
  - Stray current collection.
- *Maintenance and testing program*
  - Coordination and communication,
  - Maintenance, and
  - Testing.
- *Design criteria document for the transit agency*

## 4.1 Design Essentials

### 4.1.1 BaseLine Survey

A baseline survey from the inception of the transit system plays an essential role in the design of the rail transit system and helps develop a proper model for the operations stage. The baseline survey is an integral part of the initial design for corrosion control and consists of the following important parts:

- *Soil corrosion characteristics*: these include resistivity tests, pH tests, sulfate content, and chloride content tests. Soil corrosion characteristics like resistivity, pH, sulfate content, and chloride content determine CP needs, cement types for concrete, coatings for structures, and ground bed and grounding grid design.

- *Atmospheric corrosion characteristics*: these include weather variations, determination of pollutants, and anticipated life of galvanizing. Sources of hostile pollutants and anticipated life of galvanizing are determined using the atmospheric corrosion characteristics.
- *Utility location survey and coordination*: this includes voltage potential collection on existing utility structures, initiating the line of communication with utility owners, and actual physical survey of the nearby utilities. Existing stray current activity that may already be present from various other sources of DC is indicated by measuring voltage potentials on utility structures.
- *Surrounding infrastructure*: this includes checking for grounded connections for any metallic infrastructure near the rail line. This also includes conducting initial surveys to find out the utility and other metallic infrastructure near the rail line.
- *Education and participation*: this includes educating the relevant transit agency staff and other key stakeholders on stray current corrosion and reaching out to local corrosion societies.
- *Risk matrix*: this includes developing a risk matrix for existing and potential corrosion issues

Most of the data gathering of the baseline survey elements involves surveying the surrounding infrastructure, educating the transit agency staff, and coordinating with utility owners. Soil resistivity and its testing are important components of the baseline survey that require special attention and assist in identifying the track-to-earth resistance for the transit system. The importance of identifying and maintaining the right track-to-earth resistance for the control of stray current is emphasized in detail throughout this guidebook.

It is good transit industry practice to perform track-to-earth resistance testing as part of the baseline survey. The testing can be performed during and after construction is complete and before the revenue service starts. This process not only helps in setting up the pre-operation baseline characteristics of the system but also aids in setting up the conformance criteria. Due to the fast-track nature and budgetary constraints of DC rail transit projects, this step is mostly skipped prior to pre-revenue operation. This is unfortunate in that a solid baseline can only be established when trains are idle and the trackway is pristine. If this step is skipped before revenue service, the only way to test and establish some modicum of a baseline is during revenue service on a thoroughly cleaned and dry track. Revenue service creates dynamic conditions that render confirmation of compliance challenging and thus testing in such conditions has its drawbacks. Additionally, stray current leakage control has been found to be difficult to achieve after a system has been in service for a few years.

As with any other design or construction project, irrespective of size, a baseline survey (focused on stray current in this context) is the foremost imperative step in the data collection and fact-finding process for a transit system. Defining the design criteria for stray current mitigation and monitoring and testing for an LRT/HRT design project is equally important. However, without the baseline survey data, there are no source data or findings with which to compare the testing results.

### *Soil Resistivity*

The measurement of soil resistivity along the ROW of any transit system is essential for the corrosion control study. The soil resistivity measurements are integral in many aspects in many areas of the transit system design, including grounding, corrosivity to the underground infrastructure, and the design of the required track-to-earth resistance. Therefore, the study should include closely spaced locations along the entire ROW as well as locations of intended TPSs.

The measurement procedures should follow these industry standards:

- ASTM G51-77—for pH of soil for use in corrosion testing.
- ASTM G57—Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method.

- ASTM D1557—for moisture density relations of soils and soil aggregate, mixtures using 10-lb rammer and 18-in. drop.
- ASTM G165—for rail-to-earth resistance measurement.
- NACE (53).
- IEEE Standard 81-1983—IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System.
- BS 7430:1998—Code of Practice for Earthing.

The resistivity of soil varies widely throughout the United States and changes significantly within small areas. Resistivity is also affected by the moisture content of the soil and by the chemical composition and concentration of salts dissolved in the contained water. The influence of seasonal moisture depends on the background characteristic of the top soil layer, the resistivity of the deeper layers, and the grounding topography.

A typical soil resistivity study would include measurement locations at 500-foot spacings and at depths of 2.5 feet, 5.0 feet, 7.5 feet, 10 feet, and 15 feet. A Barnes layer analysis (53) of the soils will provide key information on the stratification of the soils, which aids in the evaluation of soil classification along the ROW. The calculated Barnes layer resistivities should be statistically analyzed using a probability distribution to determine the overall soil characteristics along the ROW or sections of the ROW. A value of soil resistivity at a given probability level should be selected to provide the design level for determining allowable earth potential gradient and stray current leakage from the rails. A design level between 80% and 90% probability is selected to cover a range of soils along the ROW.

The selected soil resistivity level can determine the allowable earth potential gradient development over a given length from the rails. This theoretical determination is made to simulate the perpendicular impact on utilities along the ROW. The allowable stray current level is determined by selecting an allowable earth potential gradient and performing the calculations for the current. The typical level of allowable earth potential gradient is about 75 millivolts over a 1,000-foot earth span perpendicular to the rails. Variations in this parameter simulate various conditions such as close proximity utility structures or long crossing or paralleling pipelines. The allowable stray current level determined in this phase of the design will be compared with the traction power load flow model to calculate the required track-to-earth resistance levels.

### *Atmospheric Corrosion Characteristics*

Climatological conditions comprise gathering local weather data including, but not limited to, temperature, relative humidity, and precipitation. Air quality data of a local area constitute determination of local area pollutants and their concentration in comparison with the appropriate local air quality standards. A matrix format and analysis in an interpretive report collate these data to validate the influence on corrosion of the rail infrastructure.

Additionally, it is important to identify the location and source of existing areas with corrosion issues within the project boundary to document existing concerns and mitigation methods implemented to control corrosion. The contractor should identify the locations of the existing corrosion issues and prepare a matrix of the locations within the track ROW.

### *Surrounding Infrastructure and Utility Location Survey and Coordination*

Maintaining effective communication with the local utility companies is also an important aspect of monitoring the performance of the SCC and mitigation system. In the case that a utility company has their own existing stray current monitoring systems or where such systems have been installed as a result of stray current mitigation activities, notifications by the utility companies that a stray current activity has occurred should be investigated and recorded.

Surrounding infrastructure and utility location survey and coordination, referred to as a stray current survey, should include the following activities:

- Perform field surveys to locate existing underground utilities and identify all structures that may be subject to corrosion due to the project within the project ROW and vicinity.
- Record stray current potential (voltage) measurements for all utility structures within the proposed project boundary, including the vicinity of maintenance and yard facilities, using a copper–copper sulfate (Cu/CuSO<sub>4</sub>) half-cell reference electrode that serves as a reference point to ground.
- Record structure-to-earth potentials for at least 24 hours at 2-second intervals at each recording location.
- Record at least 2 minutes at 2-millisecond intervals to confirm if there is significant mains-frequency voltage or other higher frequency components present at each recording location.
- Record data over approximately equally spaced locations (300 feet–500 feet) and at critical utility crossing locations within the proposed project boundary.
- Identify utilities that have cathodic protection and further designate as either impressed current or sacrificial anode cathodic protection systems.
- Coordinate with utility and pipeline owners to identify and agree on the exact location and connection point for each recording of potentials.
- Document all communications between the contractor and utility companies during the survey process on a regular basis.

### *Education and Participation*

It is important to have trained corrosion control staff on the transit agency payroll. Transit agencies are aware that stray current is a serious issue, and it would benefit them greatly if they train their staff on the fundamentals of stray current control. This would not only help address any potential stray current issues early on but would also aid the transit agency in conducting early testing of rail track.

Participation in the current local corrosion committees that exist or in any stakeholder engagements is recommended. This participation would help build awareness of stray current interference and their limits, should any exist, so that all transit agency testing activities and measurements can be compared against them and mitigations applied appropriately.

Additionally, keeping a log of the corrosion issues caused by stray current and the money spent to mitigate those corrosion problems would be extremely beneficial to the rail industry in assessing the economic and logistic burden borne by rail transit agencies as a direct impact of stray current corrosion.

### *Risk Matrix*

The following items should be further developed as part of the risk matrix during the design phases once baseline surveys have been carried out and the design is progressing, as this is the only point when the items can be ascertained:

- Detail all project-specific components both within and outside the project boundary that are at risk from stray currents from the DC transit system. Base this on survey results and means of protection for each asset and maintain a risk register that details all assets at risk from stray current.
- Identify any residual stray current.

## **4.1.2 Traction Power Model**

Designing the transit system requires understanding the transit system demand. Commercially available professional simulation models are used for the design of traction power.

These simulation models evaluate how well the design of the transit system complies with the environmental analysis for allowable stray current. The load flow program is run for various parameters associated with the transit system, including vehicle performance, traction power performance (e.g., positive distribution, negative distribution, traction power substation, or AC/DC feeders), signal performance, and schedule performance (54). The corrosion engineer uses this traction modeling data to calculate the stray current leakages, including track-to-earth resistance. This calculation requires early coordination between the traction power designer and the corrosion engineer.

Using a static simulation package is also popular, incorporating worst-case conditions of vehicle acceleration and load current to evaluate stray current leakage. The package uses the typical worst-case locations (passenger stations) to evaluate the highest possible load currents based on train size and full acceleration. As the name suggests, this method provides the worst-case analysis and will typically yield higher values of track-to-earth resistance requirements.

The following protective measures should be studied during traction power design to ensure that stray currents are maintained within the acceptable range.

### *TPS Spacing*

TPSs should be adequately spaced (preferably <1 mile apart) and provided with SCC devices to allow the connection of the negative bus to the station ground mat. The substation is arranged so that direct current does not flow into the substation structure earth. Risks from stray current relating to the earthing of equipment due to maintenance work is taken into account. The return bus bars in substations and similar installations are operated so that they are insulated from earth. When and if needed for safety reasons, a voltage-limiting device to connect between the return bus bar and earth is provided.

It is preferable to implement a test facility to allow for periodic monitoring of the stray current return to identify changing conditions associated with the track-to-earth resistance. It is ideal to provide remote monitoring systems to record the negative bus-to-earth potential, negative return shunt, track-to-earth potentials, and the stray current return circuit. The remote monitoring system should consist of either a stand-alone data acquisition module and communications package or a supervisory control and data acquisition interface.

### *Positive Distribution System*

The positive distribution system should be operated as an electrically continuous bus, with no breaks, except during emergency or fault conditions. Intentional electrical segregation of mainline, yard, and maintenance positive distribution systems should be the only type of segregation permitted. Overhead contact systems that consist primarily of support poles, the contact wire, and, where applicable, the messenger wire must be designed to minimize the generation of stray current. Third rail (conductor rail) should be on the side of the track away from the platform wherever practical. This applies to all cases except where a single track lies between two platforms.

### *Mainline Negative Return System*

The mainline running rails should be the main medium of the negative return system and thus the longitudinal resistance of the running rails should be low. The mainline running rails—including special track work, grade crossings, and all ancillary system connections—should be designed to have a minimum, uniformly distributed, in-service track-to-earth resistance. Appropriately designed insulating track fastening devices—such as insulated tie plates, insulated rail clips, direct fixation fasteners, or other approved methods—are to be in place.

A conductor rail insulated from earth, also referred to as a fourth rail, can be used for the traction return current. If this is a live part and not connected to the running rails, usually no stray currents occur. In the case of conductor rail systems with third and fourth rails, each conductor rail is to be insulated from earth depending on the nominal voltage of the system.

### *System Grounding*

It is recommended to insulate the traction supply and return circuit from earth and to preferably design the traction supply and return circuit from earth as a non-earthed, floating system. Safe earthing and bonding measures in accordance with the relevant standards and requirements should be designed to minimize potential hazards to persons or damage to systems equipment arising from the operation of electrical systems.

### *Touch Potential*

Step-and-touch potentials between the running rails and the adjacent ground or structures should be limited to 120 volts under normal circumstances (depot workshops should be limited to 60 volts). The system should be designed and installed such that this limit will not be exceeded during service operation as long as the degree of wear of the running rails remains within agreed limits. Performance of the equipment regarding stray current will, in the absence of direct evidence to the contrary, be acceptable so long as the touch potential, at all places on the system and at all times (including failure conditions), remains within 60 volts with respect to adjacent ground and structures. The agreed levels of rail-to-earth resistance are also to be maintained throughout the system. The design, however, should ensure that in normal operating conditions touch potentials lower than 60 volts are achieved.

## **4.1.3 Track Design**

Though both ballasted track and embedded track designs require equal consideration, the embedded track design necessitates a more complex level of electrical isolation as compared with ballasted track and thus demands careful design and an early contribution from the corrosion engineer. Following are some of the key elements of the track design, along with some recommended standards, that must be cross checked with the corrosion engineer at an early design level (during the traction power modeling design) to avoid potential short- and long-term stray current leakage issues.

### *Rail Resistivity and Cross Bonding*

The longitudinal resistance of the running rails should be low. The longitudinal resistance can be reduced by the use of rails with greater cross section or cross bonding of the running rails or the tracks where signaling considerations allow. Rails should be continuously welded where practicable and sufficiently well bonded across any discontinuities such as expansion joints and fish-plated joints. Bonding should also be provided to ensure continuity across switches and crossings, at which insulated cable should be used where appropriate.

There are exceptions. An exception is where block joints are needed, for which impedance bonds should be used at the ends of test lengths, where insulated rail joints shunted by removable bonds should be used; the interface between the storage and maintenance yards and the main line, where insulated rail joints should be used; and test track-isolating points, where suitable continuity bonds should be installed in a safe and reliable manner.

The two rails of each track and, where practicable, the two tracks of each route should be cross bonded at regular intervals not exceeding 500 feet using insulated cable. It is preferred to provide shunts at each substation to facilitate measurement of the current in the traction feed and return circuits from each route section served by the substation. It is also preferred to provide

shunts in the current collection cable at specific substations, which will be routed into these substations for monitoring purposes.

All fittings (clips on concrete ties) that are mounted on or mechanically connected to the rails should be either electrically insulated from the rails, insulated from earth, or, where appropriate, provided by suitable insulating joints. This includes signaling equipment.

### *Rail-to-Earth Resistance*

The insulation arrangements adopted for ballasted and embedded track should achieve a rail-to-earth resistance designated in the design criteria manual (based on the baseline survey) of the transit system after all construction works are complete, including surface finishing. The contractor should provide method statements for verifying the levels of rail-to-earth resistance achieved both on the test lengths and throughout the route, during the following stages. They are construction, postconstruction, testing and commissioning, and operation (revenue service).

### *Rail and Track Insulation*

A high level of insulation from earth of the running rails and of the complete return circuit is required when the running rails are used as part of the return circuit. To reduce stray currents, no part of the return circuit should have a direct conductive connection to metallic installations, components, or metallic structures that are not insulated from earth. This insulation of the rails can also be achieved by using the following methods:

- Rail boot construction,
- Insulation of the entire trough that carries the rail,
- Insulation of fasteners, and
- Plastic, concrete, composite, or wooden ties.

### *Isolation of Storage and Maintenance Yards*

Since the tracks in storage and maintenance yards are concentrated on a small area, no major voltage drop arises in these areas. It is recommended to electrically separate storage and maintenance yards from the running lines on both the supply and return circuits. On the supply side, each yard should be provided with a dedicated rectifier, preferably a dedicated TPS, to power movements within the yard and to meet the standing loads imposed by rolling stock. On the return side, insulated rail joints should achieve segregation. The positions of these joints should be coordinated with the positions of section breaks or overlaps in the overhead contact system, and both should be located such that the LRT system should not need to come to a stand bridging two electrical sections during foreseeable maneuvers.

Exceptions are allowed provided a stray current study proves no negative effects can occur.

### *Drainage at and Around the Tracks*

The track designer and then later the contractor should make every effort to secure and maintain effective drainage of the track throughout the route. Specifically, rainwater, leakage water from water mains, and other sources should drain quickly away from the vicinity of the rails leaving no standing water in contact with the rails or metalwork connected to them.

### *Return Cables*

Return cables connect the running rails with the TPS. The connections for the return current at substations and any other connections to the rails should be made using an insulated cable. It is preferred that the design should provide at least one representative length for insulation test purposes in each type of track form. Such test lengths should form part of the normal running

lines and be electrically isolated from the adjoining track at each end by means of insulated rail joints, to be shunted during normal operation by removable continuity bonds. The arrangements at these joints should facilitate the connection of recording equipment to each end of each test length. The test lengths should be located to afford ready access to the system earth at the nearest TPS.

### *Stray Current Leakage Path Control*

The design should be such that no stray current leakage paths form between structural units, between the structure and piped services, handrails, and other metallic components located along the track.

Electrical insulation from the transit or depot structures should be required for the following installations located along the tracks:

- Signaling equipment or their supports,
- Metal pipes,
- Lightning protection system to bridges,
- Earthing cables, and
- Sectionalizing switches, high-speed circuit breakers, and their supports.

### *Bonding of External or Nonrailway Adjacent Structures*

Critical metal structures that are not part of the transit system but that have railway safety implications should be suitably insulated or should be bonded to the traction return system via spillover devices. The number of such devices should be kept to a minimum and consistent with the required electrical performance.

Aerial track structure (bridges) or elevated structures should be designed to provide stray current isolation, rail insulation, effective drainage, and proper grounding, and should achieve the suggested rail-to-earth resistance. The implementation of SCC on bridges should follow the requirements described below.

- Provisions should be made in the reinforcing or steelwork to provide electrical conductivity in the bridge deck, parallel to and under the track.
- All longitudinal bars in the top layer of reinforcement should be tack welded at all overlaps to ensure electrical continuity and to achieve low resistance joints.
- Structural deck members should be electrically insulated from support piers and abutments.
- Any metallic handrail, anchor bolts for bridge bearing, fascia units, walkway, and the like along the bridge should be electrically insulated from the steel reinforcement in bridge beams and cross heads.

The stray current design should incorporate a suitable cable route between the connection points on the bridge deck and the points of connection to the running rails. All such connections should be made by means of insulated bolted terminals.

Underground track structures (tunnels) requirements are the following:

- Reinforcing steel in underground track structure inverts should be made electrically continuous.
- Provisions should be made in the steelwork to provide electrical conductivity, parallel to and under the track.
- Steel liner tunnel construction should be reviewed to determine the need for special measures, such as increased liner thickness, external coating systems, or CP.
- Evaluation of increased corrosion control measures should be based on the corrosivity of the local soils.

At grade crossings, where the running rails are embedded in ground, care should be taken that the value of the track-to-earth resistance does not exceed the value of the connecting tracks (neighboring tracks).

### *Utilities*

- Utility pipes and cables on the underground section of the railway, together with their fixings, should be electrically isolated from any structural reinforcing or metalwork that may carry stray current or be raised in potential by the flow of stray current, or where the pipe or cable may conduct stray current into the structural metalwork.
- All nonrailway metallic utility pipes passing through or embedded under the track should be insulated from the structure by a plastic (nonconductive) sleeve.
- All connections from external utilities to the underground section of the track, including pipes, sheaths for power cables, communications cables, and earth systems should be electrically insulated from the transit system structures and systems.
- Corrosion control requirements for buried utilities installed by the utility owner as part of transit construction should be the responsibility of the individual utility owner.
- The electrical continuity of utility structures (e.g., duct banks or steel casings) is essential. The requirements for determining the proper electrical characteristics of these structures should be incorporated into the design of the structure.

## **4.2 Stray Current Control**

Based on the literature review and verification through actual survey and testing of selected transit agencies in earlier sections of this guidebook, it is evident that SCC starts with the notion of “control at source.” Mitigation of the stray current, the collection of stray current leakage, and then finally the ongoing planned maintenance and testing of the tracks should subsequently follow. The following sections further emphasize the measures adopted and discussed previously for SCC followed by mitigation and collection techniques.

### **4.2.1 Control at Source and Isolation Techniques**

- Floating or ungrounded system,
- Designing traction supply circuits with low resistance,
- Designing traction return circuits with high resistance,
- Increasing the cross-sectional area/size of the rail (90–120 pounds, 40–80 m $\Omega$ /km),
- Maintaining a continuous electrical path for the negative current by using continuously welded rails,
- Using frequent cross bonding (250–500 feet),
- Using substation spacing (<1 mile or between >1 mile and <2 miles),
- Applying coatings to the affected structure to reduce the overall level of stray currents in the structure due to an increase of the structure-to-soil resistance. Coatings must have established performance records for the intended service and be compatible with the base metal to which they are applied:
  - Coating the rail trough of the embedded rail with a dielectric insulating material to act as a barricade to other connecting materials.
  - Coating of the rail surface with a dielectric insulating material (epoxies such as coal tar—special cases only). A number of precautions are typically followed if epoxy coated rail (ECR) is used for SCC. Care is taken during placement of the rails to minimize coating damage, because ECR will corrode at an accelerated rate at epoxy coating flaws (holidays).

- Using sealants to seal all gaps with a polysulfide, polyurethane, or silicone sealant that provides a nonconductive path between the rail and surrounding earth.
- Isolating yards and storage areas.
- Isolating other structures so there is no unintentional direct metal contact with stray current sources or other metal structures:
  - Insulated fastener clips,
  - Insulating direct fixation fasteners,
  - Maintaining the ballast at a minimum of 1 in. below the bottom of the rails and preferably at 2 in.,
  - Using elastomeric rail boot,
  - Filling the entire trough of the embedded rail with dielectric polyurethane or a combination of other suitable material (like cork or polyurethane), and
  - Insulating the anchor bolts that penetrate beyond the insulated rail trough
- Providing metal or fiber reinforced U-shaped boxes for the rail trough with cork spacers to align the rail and fill the gaps in the trough.
- Using high resistivity concrete mixes with mineral admixtures (chloride free—this can also be part of a mitigation measure).
- Using corrosion-resistance steel or reinforcing steel with improved corrosion resistance, such as stainless steel and galvanized steel. However, they are not typically considered adequate protection against stray current-induced corrosion. Galvanized steel can only provide corrosion protection to the base steel for a limited time.

Precautions should be taken so that no conductor rail will connect to earth so as to cause impermissible touch voltages on the running rails or cause a risk of fire or thermal damage to equipment.

#### 4.2.2 Mitigation

##### *CP System or Sacrificial Anode*

Although insulation of the metal (utility pipe) if perfectly applied and maintained gives decent protection against stray current corrosion, defects in insulation are unavoidable. Because of the defects, the current tends to be concentrated in the small defect area where corrosion can take place at a relatively high rate. Therefore, it is preferable to supplement the insulation with the CP of the system.

For a steel structure or pipe, it is preferable to keep the potential between 0.85 volts and 2 volts negative to soil; damage such as hydrogen embrittlement or disbonding of insulation may take place at higher negative voltages.

##### *Drainage Bonds*

In the case of anodic interference, a drainage bond between the structures may be considered to limit the positive potential shift to within the limits. If necessary, a resistor may be included to restrict the current flow. This option is implemented in rare scenarios when other alternatives cannot be used, and extra care should be used during the design.

##### *Impressed Current CP System*

Impressed current CP has been applied to most types of reinforced concrete structures in all types of conditions. CP applied to an RC structure can become the source of stray current to another part of the structure or to another structure in the vicinity, and thus needs to be carefully analyzed before implementing.

### 4.2.3 Stray Current Collection

There are situations in which mitigation measures must be augmented by the use of collection systems (like steel collection mats). For example, in high-traffic urban areas and areas where utilities and other metal structures are more concentrated, it is recommended to increase the rail-to-earth resistance by providing secondary measures to overcome the rail boot defects.

These collection mats are used to intercept and retain stray current for embedded track sections that are laid on concrete slabs with steel reinforcement such as tunnels and viaduct. In such instances, a stray current collection mat in the concrete below the tracks provides a low resistance path to intercept and retain the stray current leaving the rails. These collection mats must be continuously bonded together along their length to provide the stray current with a low resistance path. Insulated cables are provided between the mesh and the respective traction substation to offer a controlled path for the return of the stray current from the mesh to the negative bus of the traction substation instead of the alternate paths through earth. These insulated cables, usually copper, should directly connect to the mat at a regular interval of 300 to 1,000 feet (100 to 300 m) and carry the current to the point where it re-enters the substation or the running rail. This alleviates corrosion damage to supporting and third party infrastructure.

The stray current collection system should fundamentally provide electrical continuity in the reinforcement, with drain-off cables to a stray current collection cable. These cables should be electrically continuous and looped into the substations for monitoring purposes. This provision should apply to all track forms within the areas of stray current leakage. In the areas other than the ones previously mentioned, the designer may choose to provide a reinforced concrete track slab, in which case a stray current collection system should also be provided. A recommended method for providing the required electrical performance is to weld together sufficient lengths of the reinforcing rods of the concrete slab, principally parallel to but also at right angles to the track, to form a mesh with a conductivity parallel to the rails. Alternatively, a recommended method is to incorporate a proprietary preformed steel mesh into the track slab, provided it can be demonstrated to have equivalent electrical characteristics. An insulated stray current collector cable per route, having a conductivity at least equal to that of a 70 mm<sup>2</sup> copper conductor, should be run over all parts of the route containing a stray current collection system.

A dedicated duct should be provided for the stray current collection cable wherever a stray current collection mat is to be provided. Connections to the stray current collection cable should be made at intervals not greater than every 1,000 feet (300 m) in a roadside watertight recess. The design of the recesses should allow easy access for monitoring and should where practical be located outside the swept path of the LRT.

During the design of the collection mat, it must be assumed that all the current will transfer from the mat, which is located directly under the rails, to the collector cables and then to the substation. The stray collection mats are generally recommended where stray current leakage is considered to be high. Extremely high efficiencies can be achieved when the material surrounding the stray current collection system is highly resistive. At low soil resistivity, a stray current collection system with a high efficiency is more challenging to achieve. In such cases, it may be more economical to consider other ways to reduce the stray current level at the source, such as insulating the entire trough that carries the rails or in combination with high resistivity concrete. Alternatively, for low resistivity soils it may be efficient to place the rail in the rubber boot, fill the entire trough, and insulate the anchor bolts that penetrate beyond the rail trough. A detailed analysis and design are required to control the impact of stray currents on these structures.

### *Conclusion*

Use of the previously mentioned SCC techniques varies on a case-by-case basis and their individual or combined use largely depends on the environment and geographical location of the tracks within the transit system.

Following are various other methods or techniques that are used as stand-alone or in combination with each other to achieve SCC:

- Diode earthed and solidly earthed schemes,
- Grounded systems and substations,
- Insulating switch machines at the switch rods,
- Properly insulating switch blower machines and their ducting,
- Insulating the impedance bond tap connections from the housing case,
- Placing substations near points of maximum train acceleration,
- Maintaining electrical continuity in tunnel liners and reinforcing steel,
- Epoxy coated reinforcement (not common), and
- Providing isolation transformers to supply traffic signals, roadway lighting, and light rail stops near light rail tracks.

## **4.3 Maintenance and Testing Program**

It is important to conduct regular inspections and testing of the tracks, including any mitigation techniques installed by the transit system, to ascertain that the stray current leakage is within limits and the mitigation measures are operational as designed. Coordination and communication with utilities, other infrastructure owners, and potential stakeholders in the vicinity is an important component to the success of a robust maintenance and testing program.

### **4.3.1 Coordination and Communication**

The development of a coordinated effort to sustain effective SCC requires education, communication, and cooperation of all stakeholders and concerned parties. Communication is the foundation of the effort to achieve and maintain effective SCC. Thus, it is essential to maintain regular exchange of information between the interested parties to develop an overall sustainability of effective and efficient SCC. As presented in earlier sections of the report, some of the agencies carry out pipe-to-soil potential measurement on the utility lines that cross their tracks and so do the utility owners. This redundant testing is a costly and inefficient duplication of efforts that can be avoided if such entities would coordinate and collaborate beforehand to ascertain that one consultant is hired to conduct the testing and implement subsequent mitigation measures, if needed.

### **4.3.2 Maintenance and Monitoring**

For ballasted tracks it is important to maintain the ballast at a minimum of 1 in. below the bottom of the rails (preferably at 2 in.), which is difficult to maintain at all times. Considering the operation frequency of the trains, a scheduled maintenance plan is vital to maintain the ballast levels. For embedded tracks, the rubber boot is the most widely used, cost-effective, and efficient mitigation method. The rail rubber boot, if installed and maintained properly, typically does not require any costly modifications. However, rail rubber boots inevitably end up getting damaged due to heavy wear and tear in urban surroundings coupled with the periodic upkeep required for track systems. Such unpreventable wear and tear warrants regular maintenance to be an essential element of the SCC regime.

The key fundamental maintenance essentials for ballasted and embedded track system must include the following:

- Maintain the ballast at a minimum of 1 in. below the bottom of the rails (preferably 2 in.).
- Maintain rail isolation from all metal objects.
- Maintain clean and dry tracks (control vegetation and sweep away the dirt and debris).
- Perform regularly scheduled visual inspection of the tracks.
- Maintain continuous welded rail and avoid rails cracks and gaps at rail joints.
- Check for voids or loose connections at the boot sleeves (where boot overlaps).
- Maintain proper drainage around the rail boot and the tracks.
- Perform regularly scheduled testing of the tracks.

Figure 23 shows an example of maintenance work on a local LRT track. Here the rubber rail boot has been removed from a section of the track to allow room for rail lubrication equipment to help reduce wear of the rail on curves. In this particular example, since the isolation of the track was compromised due to the removal of the rubber boot, thus a polyurethane compound (Iso-flex) was used to provide the required nonconductive membrane between the rail and the ground (55). Because of the higher cost of this polyurethane compound compared with the rail boot, it is only used to repair smaller sections and where it is difficult to reinstall the rail boot.

Maintenance can install a permanent monitoring system in a concrete structure for monitoring stray current interference. This system performs the following tasks:

- Verifies the extent of polarization effects on reinforcing steel bars caused by stray current interference.
- Follows the performance and effectiveness of preventive measures used, such as electrical isolation systems, and monitors possible modifications with time, during the lifetime of the structure.
- Allows performance of measurements at positions that are not easily accessible during normal service.

### 4.3.3 Testing

A robust testing plan needs to be charted and then implemented to carry out the necessary upkeep of the tracks and the traction power system. Such a plan would benefit from first identifying



**Figure 23.** *Iso-flex replacing rail boot.*

the corrosion issues caused by stray current early on and then helping to mitigate those corrosion problems based on the data gathered from such testing.

- All structures that are to be electrically continuous should be tested for electrical continuity, compared with theoretically based criteria, to validate that they meet or exceed the accepted criteria.
- The transit agency and the utility operators should jointly determine the need for stray current monitoring facilities for utility structures.
- Test facilities may be installed at select locations to evaluate stray earth current effects during start-up and revenue operations.
- Testing facilities may be installed at all utility crossings with the system and on utilities that are within 300 feet (100 m) of the track and parallel to the system ROW.
- On completion of track work and before testing, commission, and revenue service of the traction supply system, the initial reference electrical condition on all facilities fitted with monitoring terminals, both on and off the railway, should be measured.
- Ongoing testing and monitoring of stray current and rail insulation, conductance, or potential should be conducted.
- Effective faultfinding methods should be incorporated and the technical specifications of instruments and equipment used to locate stray current leakage paths should be specified.

The recommendation, based on the research from the literature review and from feedback from transit agency personnel, is to conduct the testing of the entire transit system at least once every 3 years on newer systems and once every 1 to 2 years on older systems. The following tests are recommended based on the type, size, and physical environment of the system:

- Visual inspections,
- Structure or utility pipe-to-soil potential measurement,
- Track slab current measurement (ground current survey),
- Track-to-earth resistance survey, and
- Audio frequency signal tracing (where required).

### *Visual Inspection*

Visual inspections may be conducted to identify any uncharacteristic structure item or impact from other miscellaneous factors at each special track elements like bathtub, rail lubricators, switches, curves, rail and boot joints, traffic intersections, and along the entire track. These inspections help to identify concrete curb joining in the bathtub membranes, broken or missing rail clip isolation, and rail boot or polymer separations along rail lubricators. If required, conduct visual inspections in conjunction with physical testing of the tracks.

### *Structure or Utility Pipe-to-Soil Potential Measurement*

These tests are conducted to specify whether the structure or pipe is influenced by the stray current and if the current is leaving or entering the pipe. Negative potential denotes current pickup by the pipe whereas positive potential is indicative of current discharge. Table 9 provides the basis for further testing recommendations.

**Table 9. Recommended potential shift limits.**

Potential Shift (mV)	Stray Current Influence Category and Remedy
< 25	(N) Negligible
25–75	(L) Low—no further evaluation recommended
75–150	(M) Moderate—further evaluation recommended based on structure and protection levels
>150	(H) High—further evaluation recommended

### *Track Slab Current Measurement or Ground Current Survey*

Current flow in the track slab provides an insight into the magnitude and direction of the possible current leaking from the rails into the earth. Many transit agencies consider track slab current measurement as the most effective test to evaluate the current leakage, where the top layer of reinforcing steel is welded to make it electrically continuous.

Track slab current testing or electrical continuity testing should be performed by impressing a test current across a structure span and measuring the voltage drop caused by the test current. The measured resistance of the structure span is compared with a theoretical calculation of the structure span. Typical acceptance criteria for the field-measured resistance range from a maximum of approximately 110% to 120% of the theoretical value. Electrical continuity testing may be performed before concrete placement, after concrete placement for reinforced concrete structures identified for electrical continuity bonding, and as part of the maintenance testing during revenue service.

Electrical continuity testing should also be performed before and after backfilling for pipelines that require electrical continuity bonding.

### *Track-to-Earth Resistance Survey*

The track-to-earth resistance of the running rails is the primary barrier for the control of stray current discharge from the negative system and should be the primary construction acceptance test addressed by the transit agency. Testing to meet compliance with the established acceptance criteria may be performed as construction progresses to identify and correct deficiencies in an efficient and cost-effective manner.

The track-to-earth resistance test procedure depends on the track configuration. The testing procedures should generally follow the industry standard ASTM G165 but may be adjusted in some cases to suit field conditions. The basis of the test procedure is to apply a DC test current between the track section under test and a remote earth ground. The resistance values for each test point are averaged and normalized to a 1000-foot (300-m) length of track for evaluation of the criteria. The rail-to-earth resistance achieved by each test section should be tested in dry conditions on completion of construction (concrete pour) and before revenue service and compared with the initial results. Rail-to-earth resistance measurements require sections of track to be electrically isolated and cannot be performed during train traffic. Transit systems with small windows of time without train traffic may not have the resources to disconnect all bonds, track circuit leads, return cables, test, and then restore the system.

For embedded track, assurance of the track-to-earth resistance should be tested before the track is embedded. Once the rails are embedded in concrete or insulating compound it will be more difficult and costly to find and rectify any issue with the track insulation resistance.

This testing is conducted by impressing a test current with the help of 12 volt batteries at one location along the rails and measuring the track-to-earth voltage shift and then returning current spans along the rail at specified locations along the ROW. Measurements are recorded over 24 hours to document the transit agency peak and off-peak periods taken between the pipe or structure and earth, between the pipe or structure and rails, and between the negative bus and earth. The testing equipment requires multimeters, preferably two 12 volt DC batteries, an automatic timer, and cables to run between the testing stations. The main reason for this resistance test is to locate and remove any track work discontinuity and to document the long-term variations in the resistance values.

Each transit system requires different track-to-earth resistances fluctuating from 1 ohm/1,000 track feet to 1,000 ohms/1,000 track feet. Track-to-earth resistance value of

500 ohms/1,000 track feet for single track has been made known to be an achievable and reasonable value based on the literature review. This value varies for track laid on timber tie-stone ballast, concrete tie-stone ballast, embedded rail boot, and direct fixation tracks. In the case of new transit systems where insulation pads are used under the rails with concrete and wood ties, values of 500 ohms/1,000 track feet or greater are assumed. Track-to-earth resistance values of embedded tracks are generally less than the ballasted track construction and range from 100 ohms to 250 ohms/1,000 track feet. Track-to-earth resistance for direct fixation tracks is higher, ranging from 500 ohms to 1,000 ohms/1,000 track feet and may be higher. However, all these values are merely recommendations and must be calculated based on the results of the baseline survey.

### *Monitoring of Rail Potential*

It is difficult to insulate completely the rail, and the rail-to-ground resistance will drop on the rail with time thus making it important to detect insulation deficiencies early. This early detection is a necessary measure to prevent rail potential drop and is accomplished by continuously monitoring the rail potential at dedicated locations like substations and passenger stations. A change in the average potential is compared with the value of the reference situation for that system. The change in the maximum and minimum potential along the rail line will indicate the changes in the rail insulation.

Stray current monitoring data acquisition systems from different vendors are available in the market and can be installed at dedicated locations to measure the potential drop repeatedly. An average of 24-hour time interval readings are recorded to counter the varying traffic loads throughout the day. This method works continuously and does not affect train traffic.

### *Audio Frequency Signal Tracing Where Needed*

An audio frequency detector is used to locate discontinuities in the electrical circuit. The equipment includes an oscillator that converts low voltage (12 volts) DC from the battery to a stable audio frequency AC and a receiver that employs an integrated circuit amplifier. The oscillator is connected to the battery and to the rail whereas the tester walks with the receiver along the rail to locate the discontinuities. The voltage suddenly drops to a low or null level, where there is a short or discontinuity identified along the traverser distance. This is assumed to be a point directly above the contact. In areas where there may be a complicated network of continuous structures, it is difficult to pinpoint specific locations and other methods may need to be employed.

Audio frequency signal tracing results are used in conjunction with the track-to-earth resistance data to pinpoint local low-resistance areas requiring further investigation. These tests are conducted by impressing a 750-hertz signal onto the rail in various configurations and measuring the signal strength along the rails. Figure 24 shows a typical audio frequency tester.

In transit agencies that have a regular maintenance and testing plan along with correctly designed mitigation measures, it was observed that they have a better handle on stray current leakage. This makes the regular testing of the tracks an important aspect, and this cost should be included in the maintenance budgets for transit agencies.

Only a handful of the transit agencies surveyed, questioned, and tested as part of this guidebook development perform such regular testing of the tracks. It was easily recognizable from the results of the survey questionnaire that those agencies that do perform such regular testing of the tracks have fewer stray current problems.



**Figure 24.** Audio frequency test setup.

#### 4.4 Criteria Document

A thorough criteria document with corrosion control design should be prepared and used as a guide for implementing the design and maintenance requirements for stray current corrosion control and stray current mitigation systems. The document should include the procedures and evaluation criteria for rail-to-earth resistance, stray current corrosion control design, and stray current testing and maintenance guidelines.

The design criteria document should summarize the baseline survey and be updated periodically to include stray current surveys. The document should highlight the implication of the baseline survey findings on the design of corrosion and stray current mitigation systems for the transit system and underground utilities that are installed or relocated as part of the LRT system construction. The design criteria document should discuss the site specific (geographical) conditions for the transit agency, identify necessary deviations from the design criteria requirements due to site specific conditions, and provide the rationale for each deviation. The principles provided in the design criteria document are only for guidance.

#### 4.5 Chapter Summary

Assessment of the potential corrosion resulting from stray current should be an integral part of the planning and design process at the inception of all projects. Additionally, the testing of stray current corrosion must continue through the course of revenue service. Transit agencies are aware that stray current is a serious issue, and it would benefit them greatly if they train their staff on the fundamentals of stray current control. This would not only help address any potential stray current issues proactively but would also aid the transit agency in conducting early testing of rail track.

Many transit agencies do not maintain a log for stray current corrosion issues and the money spent to mitigate those corrosion problems. This kind of tracking would prove beneficial to the rail industry in assessing the economic and logistic burdens borne by the transit agencies as a direct impact of stray current corrosion. Stray current issues have been around since the first electric railways were placed into operation and can create safety hazards and have serious effects on utility structures and the transit infrastructure. Since most of the heavily

affected systems are street railways or trolleys, the areas in which the railways were built were also most likely to have underground metallic structures like utility piping, thus making it necessary to have stray current leakage control. Although stray current corrosion is more of an issue in embedded tracks and tracks with low soil resistivity, it is a concern for all kinds of track and needs to be addressed during the design, construction, and maintenance of DC-powered rail transit systems.

For embedded tracks, the design must have an electrical barrier to insulate the rail from the conductive parts having the potential of carrying the current to the earth. Even though bituminous asphalt and different mixes of concrete embedment have been used in the track design in combination with other epoxies, the rail boot has proved to be the most effective and cost-efficient SCC measure. Rail boots not only provide vibration isolation but they also buffer the rail and its supports from the surrounding structure, thereby providing resistivity to fugitive stray current. Thus, the rail boot not only protects the rail but also protects the surrounding infrastructure from corrosion. Some key benefits of the rail boot are as follows:

- Quick and easy installation without the need for specialized technical crews.
- Rail is completely electrically isolated.
- Air-borne and ground-borne noise reduction.
- Galvanic corrosion of rail foot near embedded steel structures and utilities is avoided.
- Rubber boot track system is simple to construct.
- Minimal maintenance of paved track system as compared with other techniques.

The inconsistent design of the extension of an existing system is a major contributing factor to stray current leakage. The exceptions are when the older track is electrically isolated from the new track or the older track was designed or improved to a similar or as stringent an SCC design as the new track.

In conclusion, it would be easier to implement most of the preceding isolation, mitigation, and collection options on a newer transit system with proper foresight and planning. Not all the options and recommendations discussed in this section apply to older systems or systems that are building extensions to their existing systems. It is thus the responsibility of the design engineer or consultant, in conjunction with the transit agency, to design an SCC system tailored to each unique scenario. The key to achieve a leakage-free transit system is to follow the logical sequence of the design process and then maintain a stringent maintenance and testing regime.

# Conclusions

Chapter 5 summarizes the work done in the preparation of this guidebook, presents the main conclusions, and offers some suggestions for potential future work.

## 5.1 Literature Review

Chapter 2 presents a literature review of existing work. The chapter includes a review and study of international and domestic standards discussing different practices available to the transit agencies and explains previous work on the control and mitigation of stray current corrosion. This literature review compiles the data, research, and criteria from a wide range of sources on stray current. The study and investigation encompass the review of theoretical, practical, and experimental approaches to address stray current leakage and corrosion issues in DC-powered transit systems. Although many transit agencies have their own standard criteria, the rationale behind their initial limiting voltage and current values is unknown.

Besides investigating the historical development of stray current corrosion mitigation techniques, the literature review includes the study of existing stray current testing techniques and their use within a transit system. The study team looked at design criteria manuals for various agencies around the world to help perform a comparative analysis of different norms adopted by transit agencies.

## 5.2 Transit Agency Data Assembly, Studies, and Field Testing

Chapter 3 compiles data assembled by sending questionnaires to real world, DC-powered rail transit systems inquiring about their process of SCC or their collection system. Based on the findings of the initial questionnaire, a longer questionnaire was sent to a select few agencies followed by a series of one-on-one interviews with transit agencies and corrosion consultants. The chapter also includes the findings of different SCC criteria and testing methods adopted by a diverse cross section of U.S. and international DC-powered transit agencies.

The chapter elaborates on various stray current mitigation and testing procedures and their results for a real-life transit agency and for an actual startup transit system. Reviewing and compiling the results of these questionnaires and interviews highlights that in most instances the use of the limiting values for the SCC (including the limiting values set forth for slab current testing and track-to-earth testing) are drawn from industry experience rather than from actual testing and design parameters. It is also evident that most of the agencies had not conducted pre-revenue testing and did not have a regular testing and maintenance plan. The data also indicated that transit agencies are not maintaining a log of the stray current corrosion issues

nor are they tracking the expenditure to mitigate those corrosion problems. Furthermore, most of the transit agencies interviewed relied on outside consultants to conduct their stray current corrosion testing due to limited knowledge and understanding of the issue, coupled with the absence of guidelines. Corrosion staff from all the agencies interviewed mentioned that they would like to have proper guidelines and standards and a preferred management plan for stray current mitigation.

The questionnaire and findings have been presented in a matrix format in the appendices and throughout Chapter 3. Stray current corrosion issues for three U.S. transit agencies are illustrated in the chapter.

This compilation of a range of real world data informs a unique, holistic perspective that the track-to-earth resistance for the track largely depends on isolation methods and techniques incorporated at the time of design and construction and then onward during the maintenance of tracks. The data in this chapter also highlight that testing methods and frequency of testing should be adapted based on the age of the transit system, location of the tracks, type of the track bed, type of the structure under investigation, and the source of leakage. Chapter 3 strengthens the argument for performing baseline surveys and pre-revenue testing for a startup line.

### 5.3 Recommendations and Guidelines

Chapter 4 uses the data collected from the literature review and stray current testing observations, coupled with the information gathered from the questionnaire and corrosion consultant interviews, to develop a stepwise process for achieving a uniform stray current isolation and QC for an embedded track.

This chapter highlights that it is relatively easier to implement stray current isolation, mitigation, and collection options on a newer transit system with proper foresight and planning by following the logical sequence of the design process than to maintain a stringent maintenance and testing regime on an older system.

A significant part of the work described in this guidebook addresses the design of SCC methods, sustainability of SCC, and the control of rail-to-earth voltages for DC-powered rail transit systems for North American transit agencies. The guidebook is to be used by transit agencies, design, and maintenance practitioners and to influence new system construction, extensions, and maintenance and operation of existing systems.

The guidebook includes, for the first time under one cover, the design and sustainability of SCC for DC-powered rail transit systems, with a primer that explains all significant issues in readily understandable terms for a non-technical audience. It is the first compilation of data that identifies the domestic and international body of knowledge pertaining to principles, procedures, methods, and criteria for achieving and documenting acceptable levels of stray current and rail-to-earth potential.

### 5.4 The Potential for Future Work

This synthesis report or guidebook includes recommended procedures for achieving stray current isolation and mitigation techniques. Areas were identified that may need further development. These include, but are not limited to, the following:

- *Simulation modeling to calculate and design for stray current leakage:* Use of software modeling to conduct a thorough analysis of leakage currents and their proposed mitigation techniques. The use of a stray current simulation model, along with traction power design analysis, at the

inception of DC transit system track design would prove to be an invaluable proactive step in achieving the desired SCC.

- *Material lost and cost impact:* The research scope reveals the potential corrosion impact on the structure for different scenarios and the total stray current leakage. However, key data missing are the potential costs of the SCC. This cost can be broken down into the cost to carry out the isolation to avoid the stray current corrosion design and the cost to perform potential mitigation measures once the problem is identified on an existing system. A means to ascertain these costs could help transit owners in making key decisions for providing the corrosion mitigation measures at the time of initial construction versus during the transit service or revenue phase.

The authors also identified the following areas as potential knowledge gaps during the research. The areas are touch potentials and their correlation with SCC and mitigation, equipment grounding and system grounding, optimum maintenance cycles and essentials, and methods for anonymously sharing costs and experiences across the various transit agencies.



## Acronyms

AC	Alternating Current
ANSI	American National Standards Institute
APTA	American Public Transportation Association
AREMA	American Railway Engineering and Maintenance-of-Way Association
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
BSI	British Standards Institute
CP	Cathodic Protection
CTA	Chicago Transit Authority
DC	Direct Current
DDOT	District Department of Transportation
ECR	Epoxy Coated Rail
FHWA	Federal Highway Administration
GCRTA	Greater Cleveland Regional Transit Authority
GPS	Global Positioning System
HRT	Heavy Rail Transit
IEEE	Institute of Electrical and Electronics Engineers
IET	Institution of Engineering and Technology
JRC	Joint Rail Conference
LA METRO	Los Angeles Metropolitan Transportation Authority
MBTA	Massachusetts Bay Transportation Authority
MD MTA	Maryland Transit Administration
METRO	The Metropolitan Transit Authority of Harris County, Texas
MTA	Metropolitan Transit Authority
NACE	National Association of Corrosion Engineers
NASEM	National Academies of Sciences, Engineering, and Medicine
NCTRDP	National Cooperative Transit Research and Development Program
NY MTA	New York Metropolitan Transit Authority
NYCT	New York City Transit
OCS	Overhead Catenary System
QC	Quality Control
ROW	Right-of-Way
SC	Stray Current
SCADA	Supervisory Control and Data Acquisition
SCC	Stray Current Control
SEPTA	Southeastern Pennsylvania Transportation Authority
STD	Standard
TCRP	Transit Cooperative Research Program

TF	Track Feet
TPS	Traction Power Substation
TTC	Transportation Technology Center
TA	Utah Transit Authority
UTA TRAX	Utah Transit Authority Transit Express
WMATA	Washington Metropolitan Area Transit Authority

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## APPENDIX A

# Short Survey

Please check the option that applies to help understand the stray current corrosion and mitigation measures taken by the transit agency.

1. Transit agency name, Contact person name, and Title.

2. Type of power used for the system?

a. AC       b. DC       c. Other  (specify) \_\_\_\_\_

3. Type of rail transit system and total miles for each system?

a. HRT  \_\_\_miles    b. LRT  \_\_\_miles    c. Trolley/Commuter  \_\_\_miles    d. Other  (specify) \_\_\_\_\_

4. What mode is used for the power distribution to the system?

a. Third Rail       b. Overhead Catenary       c. Other  (specify) \_\_\_\_\_

5. Operational Voltage?

a. 650 volts     b. 750 volts       c. Other  (specify) \_\_\_\_\_

6. Physical environment of service?

a. Semi Urban     b. Urban (shared ROW)     c. Urban (exclusive ROW)     d. Other  (specify) \_\_\_\_\_

7. Is there an embedded section of track for the transit agency?

a. Yes       b. No       c. Other  (specify) \_\_\_\_\_

8. Are the pedestrian stations located in the same area as traction power stations?

a. Yes       b. No       c. Other  (specify) \_\_\_\_\_

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9. What is the average spacing between stations?  
 a. < 1 mile       b. > 1 but < 2 miles       c. Other  (specify) \_\_\_\_\_
10. Was the baseline survey conducted before the revenue service?  
 a. Yes       b. No       c. Other  (specify) \_\_\_\_\_
11. Is there a maintenance and testing plan in place for the system?  
 a. Yes       b. No       c. Other  (specify) \_\_\_\_\_
12. What is the preferred track-to-earth resistance for the system?  
 a. 250 ohms /1000 ft.       b. 500 ohms /1000 ft.       c. 1000 ohms /1000 ft.       d. Other  (specify) \_\_\_\_\_
13. Does the transit agency currently have stray current corrosion issues?  
 a. Yes       b. No       c. Don't know       d. Other  (specify) \_\_\_\_\_
14. How would you rate your stray current control effort/program?  
 a. Non-existent       b. Poor       c. Good       d. Very good       e. Excellent / "World Class"
15. What value would a rail transit stray current control best practice guide document have to you?  
 a. No/little value       b. Some value       c. High value
16. Are you willing to participate in a more detailed questionnaire to provide further information about the stray current corrosion issues and mitigation methods? If you would like to nominate someone else from your company then please provide their name.  
 a. Yes       b. No       c. Contact Name  \_\_\_\_\_

E-mail \_\_\_\_\_

Telephone \_\_\_\_\_



## APPENDIX B

# Responses from Transit Agencies

Serial #	Question	Response from Transit Agencies				
		Transit Agency 1	Transit Agency 2	Transit Agency 3	Transit Agency 4	Transit Agency 5
1	Transit Agency Name, Contact Person Name, and Title					
2	Mode used for power distribution, operational voltage, and the type of power for the system?	Overhead Catenary – 750V dc	Third Rail – 600V dc	LRT = Overhead Catenary & HRT = Third Rail – 750V dc	Third Rail – 1000V dc	Overhead Catenary – 750V dc
3	Type and Length of each system (in miles), by type?	7.5 miles of LRT	660 miles of LRT	88 miles of LRT & 22.5 miles of HRT	110 miles of LRT (double track)	48 miles of LRT
4	What is the physical environment of your service area?	Urban - Downtown & Business District	Underground, Elevated & exclusive ROW	Semi Urban, Urban shared & Urban exclusive ROW	Urban exclusive ROW (Semi Urban)	Urban, Semi Urban & railroad corridors
5	Is there an embedded section of track for the system?	Yes	Yes	Yes	Yes	Yes
6	What is the average spacing of substations on your system?	> 1 but < 2 miles	> 1 but < 1.25 miles	> 1 but < 1.5 miles (depends on the configuration necessary)	> 1 but < 2 miles (with few longer sections)	> 1 but < 2 miles
7	Are the pedestrian stations located in the same area as traction power stations?	Yes		No	Yes	Yes
8	Was the baseline survey conducted for the system?	After the revenue service	No	Yes	No	Yes
9	Do you routinely perform stray current control testing/monitoring for operating sections of your rail systems?	Yes	No, unless a stray current problem is suspected or reported	No, unless a stray current problem is suspected or reported	Yes	Yes
10	What is the preferred track-to-earth resistance for your system?	250 ohms/1000 track feet		300 ohms/1000 track feet - Embedded track 500 ohms/1000 track feet - Ballasted track	500 ohms/1000 track feet	250 ohms/1000 track feet
11	Does the transit agency currently have stray current corrosion issues?	No	No	Don't know	Yes	Don't know
12	How would you rate your stray current corrosion mitigation effort/program?	Very Good			Good	Good
13	What value would a rail transit stray current best practice guide document have to you?	Some value	Some value		High value	Some Value
14	Are you willing to participate in a more detailed questionnaire to provide further information about the stray current corrosion issues and mitigation methods?	Yes	Yes	Yes	Yes	Yes

Serial #	Question	Response from Transit Agencies				
		Transit Agency 6	Transit Agency 7	Transit Agency 8	Transit Agency 9	Transit Agency 10
1	Transit Agency Name, Contact Person Name, and Title					
2	Mode used for power distribution, operational voltage, and the type of power for the system?	Overhead Catenary – 750V dc	Third Rail & Overhead Catenary – 600V dc	Overhead Catenary – 750V dc	Third Rail & Overhead Catenary – 650V dc	Overhead Catenary – 750V dc
3	Type and Length of each system (in miles), by type?	58.5 miles of LRT	22 miles of LRT, 50 miles of HRT	42 miles of LRT	30 miles of LRT, 20 miles of HRT	60 miles of LRT
4	What is the physical environment of your service area?	Semi Urban, Urban shared, & Urban exclusive ROW	Urban exclusive ROW	Semi Urban, Urban shared, & Urban exclusive ROW	Urban shared & exclusive ROW	Semi Urban, Urban shared, & Urban exclusive ROW
5	Is there an embedded section of track for the system?	Yes	Yes	Yes	Yes	Yes
6	What is the average spacing of substations on your system?	> 1 but < 2 miles	< 1 mile	> 1 but < 2 miles	< 1 mile	< 1 mile
7	Are the pedestrian stations located in the same area as traction power stations?	Yes	No	Yes	Yes	Some are
8	Was the baseline survey conducted for the system?	Yes	Yes	Yes	No	Yes
9	Do you routinely perform stray current control testing/monitoring for operating sections of your rail systems?	Yes	Yes	Yes	Periodic rail continuity testing of LRT	Yes
10	What is the preferred track-to-earth resistance for your system?	500 ohms/1000 track feet	1000 ohms/1000 track feet	500 ohms/1000 track feet	Not Specified	200 ohms/1000 track feet - Embedded track 500 ohms/1000 track feet - DF and Ballasted track
11	Does the transit agency currently have stray current corrosion issues?	Yes	No	Don't know	Yes	Yes
12	How would you rate your stray current corrosion mitigation effort/program?	Poor	Non-existent	Poor	Good	Very Good
13	What value would a rail transit stray current best practice guide document have to you?	High value	Some value	High value	Some value	High value
14	Are you willing to participate in a more detailed questionnaire to provide further information about the stray current corrosion issues and mitigation methods?	Yes	Yes	No	Yes	Yes

Serial #	Question	Response from Transit Agencies			
		Transit Agency 11	Transit Agency 12	Transit Agency 13	Transit Agency 14
1	Transit Agency Name, Contact Person Name, and Title				
2	Mode used for power distribution, operational voltage, and the type of power for the system?	Overhead Catenary – 750V dc	Third Rail – 750V dc	Third Rail & Overhead Catenary – 750V dc	Third Rail & Overhead Catenary – 600V dc
3	Type and Length of each system (in miles), by type?	26 miles of LRT	103 miles of HRT	15 miles of HRT, 26 miles of LRT	189 miles of LRT, 42 miles of HRT
4	What is the physical environment of your service area?	Urban shared ROW	Semi Urban & Urban exclusive ROW	Semi Urban, Urban Shared ROW, and Urban Exclusive ROW	Urban shared & exclusive ROW
5	Is there an embedded section of track for the system?	Yes	Yes	Yes	Yes
6	What is the average spacing of substations on your system?	> 1 but < 2 miles	> 1 but < 2 miles	> 1 but < 2 miles	> 1 but < 2 miles
7	Are the pedestrian stations located in the same area as traction power stations?	Some are	Some are	Some are	Some are
8	Was the baseline survey conducted for the system?	Yes	Yes		On some lines
9	Do you routinely perform stray current control testing/monitoring for operating sections of your rail systems?	Yes	Yes		Yes
10	What is the preferred track-to-earth resistance for your system?	100 ohms/1000 track feet - Embedded track 250 ohms/1000 track feet - Ballasted track	500 ohms/1000 track feet - Direct Fixation track 50 ohms/1000 track feet - Tie & Ballasted track	1000 ohms/1000 track feet	500 ohms/1000 track feet
11	Does the transit agency currently have stray current corrosion issues?	No	Yes	Yes	Yes
12	How would you rate your stray current corrosion mitigation effort/program?	World Class	Good	Good	Very Good
13	What value would a rail transit stray current best practice guide document have to you?	High value	Some value	Some value	High value
14	Are you willing to participate in a more detailed questionnaire to provide further information about the stray current corrosion issues and mitigation methods?	Yes	Yes		Yes

Serial #	Question	Response from Transit Agencies				
		Transit Agency 15	Transit Agency 16	Transit Agency 17	Transit Agency 18	Transit Agency 19
1	Transit Agency Name, Contact Person Name, and Title					
2	Mode used for power distribution, operational voltage, and the type of power for the system?	Overhead Catenary – 650V dc	Overhead Catenary – 750V dc	Third Rail – 750V dc	Third Rail – 750V dc	LRT = Overhead Catenary – 650V dc, HRT = 1500V dc
3	Type and Length of each system (in miles), by type?	15 miles of LRT	43 miles of LRT	20 miles of LRT (double track)	25.5 miles of HRT	497 miles of HRT, 311 miles of LRT
4	What is the physical environment of your service area?	Urban exclusive and shared ROW	Urban exclusive and shared ROW	Urban exclusive ROW	Semi Urban	Semi Urban, Urban shared, and Urban exclusive ROW
5	Is there an embedded section of track for the system?	Yes	Yes	Yes	No	Yes
6	What is the average spacing of substations on your system?	> 1 but < 2 miles	> 1 but < 2 miles (with one longer than 2 mile section)	> 1 but < 2 miles	< 1 mile	> 1 but < 3 miles
7	Are the pedestrian stations located in the same area as traction power stations?	Yes	Yes	Yes	Some are	Some are
8	Was the baseline survey conducted for the system?	On the new lines	Yes	On some lines		No
9	Do you routinely perform stray current control testing/monitoring for operating sections of your rail systems?	No	Yes	Yes	Yes	Yes
10	What is the preferred track-to-earth resistance for your system?	500 ohms/1000 track feet	Between 5 to 20 ohm km (single rail)	As per European Standard EN 50122-2, conductance per unit length for a single track is 0.5 S/km		
11	Does the transit agency currently have stray current corrosion issues?	Yes	No	No	Yes	Yes
12	How would you rate your stray current corrosion mitigation effort/program?	Non-existent	Very Good	Good	Good	Very Good
13	What value would a rail transit stray current best practice guide document have to you?	High value	Some value	Some value	High value	Some value
14	Are you willing to participate in a more detailed questionnaire to provide further information about the stray current corrosion issues and mitigation methods?	Yes	Yes	No	Yes	Yes



## APPENDIX C

# Long Questionnaire

***The following questions have been prepared with multiple choice answers for ease of use but should in no way limit your response. We do not have all the answers so the proper response for your agency may not be listed. Please detail the response under "Other". You may use as much space as necessary.***

1. Transit agency name, contact person name, email, title, and telephone number.
  
2. Any special weather condition criteria or design requirement? For example, special concrete additives, switch heating units, reduced service, different seasonal track-to-earth resistances, etc.
  
3. What is the age of the system (Please define all systems and lines. Take as much room as needed)?
 

a. Light rail Line 1, (name) ____ - ____ years Line 2, (name) ____ - ____ years Line 3, (name) ____ - ____ years	b. Heavy rail Line 1, (name) ____ - ____ years Line 2, (name) ____ - ____ years
c. Trolley / Commuter - ____ years	d. Other _____ - ____ years
  
4. What is the length of the total system (provide breakdown by system type)?
 

a. Light rail miles ____ c. Trolley / Commuter ____	b. Heavy rail miles ____ d. Other: _____ - miles
--	---
  
5. What are the type, size and cross-section of the rail used? If sketches are available, please send along with this response.
  
6. Number of substations? Please breakdown by service line.
  
7. What is the average spacing of the substations? Please breakdown by each service line.
  
8. What is the largest spacing between two power stations?

9. What is the spacing between the power stations and passenger stations, if any?
10. What tests were conducted in the baseline survey (pre-revenue service testing)? Which of those tests were recommended for future maintenance testing?
11. What guidelines and/or national/international standards were followed for the baseline survey?
12. What were the limiting values identified for track-to-earth resistance during the baseline survey?
13. What were the limiting values identified for track-to-earth resistance during subsequent maintenance tests?
14. What design measures were incorporated to mitigate stray current corrosion?
15. What other design measures/stray current provisions are incorporated to control stray current leakage?
  - a. None, per se
  - b. Ungrounded negative return circuit
  - c. Diode grounded negative return circuit
  - d. Insulated rail fasteners
  - e. Structure stray current drainage
  - f. Utility stray current drainage
  - g. Electrically bonded reinforced concrete structures
  - h. Yard traction power positive and negative distribution circuits normally electrically isolated from mainline
  - i. Shop traction power positive and negative distribution circuits normally electrically isolated from yard
  - j. Electrical segregation of mainline traction power (positive and or negative distribution circuits)
  - k. Others \_\_\_\_\_
16. Is there a program for track maintenance? If yes, what is it?
17. Do you routinely perform stray current control testing/monitoring for operating portions of your rail system?
  - a. No, not at all
  - b. No, unless a stray current problem is suspected or reported
  - c. Yes, typically on an annual basis
  - d. Yes, typically every few years
  - e. Yes (indicate typical frequency) – every \_\_\_ years

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18. Do you have written procedures for your stray current control testing, monitoring and maintenance? If yes, please send a copy with this response.
- a. No                      b. Yes, general framework only                      c. Yes, including detailed procedures
19. What is the track-to-earth resistance for the system currently? Please breakdown by service line if there is a difference.
20. Is track-to-earth resistance measured as part of the testing/maintenance plan?
21. Can stray current corrosion be differentiated from other corrosions to the metal structures for your system?
- a. No                      b. Yes
22. Have you encountered stray current corrosion-related problems on the system? If yes, how so?
- a. No                      b. Yes
23. Who is responsible (entity) for the stray current corrosion control, maintenance, testing and monitoring?
- a. We do not have a stray current control program, per se                      b. Engineering Department  
c. Electrical Maintenance Department                      d. Trackwork Maintenance Department  
e. Other: \_\_\_\_\_
24. Do neighboring utilities currently believe they are experiencing transit-caused stray current effects?
- a. Don't know                      b. No                      c. Yes, things are under control  
d. Yes, and they have reported problems that have not yet been addressed  
e. Other: \_\_\_\_\_  
f. Additional Comments: \_\_\_\_\_
25. When was the first stray current corrosion-related problem noticed? When was it repaired?
26. What measures were taken to control and/or remove the stray current corrosion issues?
27. How long have the repairs been on-going?
28. Is historical corrosion and repair data available? Can it be reviewed?
29. Is there a log of the maintenance conducted to address the stray current corrosion?

30. Is there a log of total cost of the corrosion repairs to-date? Can they be reviewed?
31. Currently, are there any stray current corrosion problems?
32. Have stray current corrosion issues caused you to modify your maintenance plan or stray current control methodology? Can the maintenance plan be reviewed?
33. Has the present stray current corrosion problem been repaired/fixed?
34. What was the total cost for the most recent stray current corrosion repair?
35. How many stray current corrosion repairs are typically made per year?
36. Has the frequency of stray current corrosion related problems decreased or increased with time?
37. How many route miles of light or heavy rail are currently under construction and or planned over the next few years? (Check all that apply and make additions, as needed)
- a. Don't know
  - b. Nothing currently under construction
  - c. Nothing planned over the next few years
  - d. LRT miles \_\_\_\_\_
  - e. HRT miles \_\_\_\_\_
  - f. Trolley / Commuter \_\_\_\_\_
  - g. Other: \_\_\_\_\_ miles
38. For in-progress transit construction and/or planned extensions over the next few years (if any), what stray current control provisions are expected and/or engaged? (Check all that apply and make additions, as needed)
- a. None, per se
  - b. Don't know
  - c. Ungrounded negative return circuit
  - d. Structure stray current drainage
  - e. Utility stray current drainage
  - f. Electrically bonded reinforced concrete structures
  - g. Other 1: \_\_\_\_\_
  - h. Other 2: \_\_\_\_\_
  - i. Other 3: \_\_\_\_\_
39. What is the latest total annual operating cost for the rail system?
40. What part of the total operating cost is for non-vehicle maintenance?

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41. What is the estimated annual cost for stray current corrosion repairs excluding the consultant fee?
42. What do you estimate the repair costs due to stray current corrosion to be for the next 5 years?
43. What percentage of this cost will be the consultant fee?
44. Is there a certain budget to address the on-going stray current corrosion issues?
45. Is the transit system still in need of any repair/mitigation to control the stray current issues?
46. “Lessons learned” from the stray current corrosion incidents and/or repairs?
47. What changes or modifications other than above lessons learned would you like to see or recommend to the industry?
48. Is there a local electrolysis committee to discuss stray current issues?
49. Do you participate in this local committee?
50. What stray current design specifications or manuals have been the most helpful in the past? Which ones have guided your design and maintenance methodology?
51. Do any Federal guidelines impact your design and maintenance approaches? Are there any that have a negative impact?



## APPENDIX D

# Summary of Agency Response Findings

S. No.	Question	Transit Agency 1	Transit Agency 2	Transit Agency 3	Transit Agency 4
1	Transit Agency Name, Contact Person Name, and Title				
2	Any special weather condition criteria or design requirement? For example, special concrete additives, switch heating units, reduced service, different seasonal track-to-earth resistances, etc.	Special Cold weather measures. Corrosion issues due to melting of ice.	Hot and Humid weather. There are times with limited and/or no service due to heavy rains and poor drainage.	No special criteria	No special criteria
3	How old is the transit system? (which year was it put in service?)	23 - Years (In service since 1994 with various new routes since then)	13 - Years (In service since 2004 with various routes since the initial start)	27 - Years (In service since 1990 with various new routes since then)	113 - Years (In service since 1904 with various routes since the initial start)
4	What is the length of the total system (provide breakdown by system type)?	48 miles of LRT	7.5 miles of LRT	88 miles of LRT and 22.5 miles of HRT	660 miles of LRT
5	What is the type, size, and cross-section of the rail used? Provide sketches along with your response if available.		115RE	115RE, Ri59/13	115RE, Ri59/13, and Ri52
6	Number of substations and break down by service line		Total = 8	Total = 120	Total = 214
7	What is the average spacing of the substations?	> 1 but < 2 miles	> 1 but < 2 miles	> 1 but < 1.5 miles (depends on the configuration necessary)	> 1 but < 1.25 miles
8	What is largest spacing between the two substations?	> 1.5 mile	< 2 miles	< 1.5 miles	< 1.25 miles
9	What is the spacing between the substations and passenger stations, if any?	mostly at the same location	mostly at the same location	No correlation	1 to 1.25 miles

S. No.	Question	Transit Agency Name			
		Transit Agency 1	Transit Agency 2	Transit Agency 3	Transit Agency 4
10	What tests were conducted in the baseline survey (pre-revenue service testing)? Which of those tests were recommended for future maintenance testing?	Baseline testing is conducted on the newer lines	No baseline testing was done on the older line(s) before revenue service. However, the tests were conducted immediately after the revenue service. The tests were also carried out on the lines currently under construction	No baseline testing was done on the older lines. The goal is to conduct baseline testing before revenue service on the lines currently under construction	Not sure
11	What guidelines/standards (both national and international) were followed for the baseline survey?	Transit agency design, criteria and ASTM standard	Transit agency design, criteria, ASTM standard, NACE - Peabody and Cathodic Protection Survey Procedures	Consultant is currently in the process of developing a criteria document for the transit agency	N/A
12	What were the limiting values identified for track-to-earth resistance during the baseline survey?	250 ohms/1000 track feet	250 ohms/1000 track feet	300 ohms/1000 track feet - Embedded track 500 ohms/1000 track feet - Ballasted track	
13	What were the limiting values identified for track-to-earth resistance during subsequent maintenance tests?	250 ohms/1000 track feet	250 ohms/1000 track feet	Track-to-earth measurements are not part of regular scheduled maintenance.	5 ohms/1000 track feet
14	What design measures were incorporated to reduce stray current corrosion?	LRT Design Criteria followed	Rebar system within the track slab, continuous welded rail, insulated pads, cross bonding, and rail boot	Sacrificial anodes, insulated pads and direct fixation. Cross bonds installation	Continuously welded rail, non grounded system

S. No.	Question				
		Transit Agency Name	Transit Agency 1	Transit Agency 2	Transit Agency 3
15	What other design provisions are incorporated to control stray current leakage?	Extruded rubber on both sides	Bathtub membrane in the special track work sections.	Active and Passive Method-insulated plates and fasteners, rail boot	Insulated Pads
16	Is there a program for track maintenance? If yes, what is it?	Transit agency design criteria requirements are followed	Yes, visual inspections are conducted. Transit agency also has a maintenance manual that the staff follows	Yes, visual inspections are conducted	Yes, visual inspections are conducted
17	Do you routinely perform stray current control testing/monitoring for operating sections of your rail systems?	No, unless a stray current problem is suspected or reported	Yes regular testing of the tracks is carried out by Consultant along with visual monitoring by transit agency staff	No there is no routine program for testing or monitoring. Currently working on getting one.	No, unless a stray current problem is suspected or reported
18	Do you have written procedures for your stray current control testing, monitoring and maintenance? If yes, please send a copy with this response.	No, but there is a design criteria manual	No, but there is a design criteria manual. Additionally, consultant follows a standard testing plan that has been carried out for years now	Didn't have any monitoring and/or maintenance program in the past. Currently working on developing one	No, The stray current leaks are detected and reported by utility providers and other third parties.but there is a design criteria manual
19	Is track-to-earth resistance measured as part of the testing/maintenance plan?	LRT design criteria followed	LRT design criteria followed	No	No
20	What is the track-to-earth resistance for the system currently? Please breakdown by service line if there is a difference.	Should be: 250 ohms/1000 track feet	Equal to and/or above the limited resistance as defined above	Not measured for all lines. However, one of the newer lines was recently measured at 250 ohms/1000 feet of track	N/A

S. No.	Question				
		Transit Agency 1	Transit Agency 2	Transit Agency 3	Transit Agency 4
21	Can stray current corrosion be differentiated from other corrosions to the metal structures for your system?	Yes	Yes	Yes	Yes
22	Have you encountered stray current corrosion-related problems on the system? If yes, how so?	Yes - Hand rails on the high bars corrode	No - Control and mitigation measures are keeping stray current under control	Yes - we receive notification from the utility owners and other third parties	Yes - reported by utility companies in the vicinity of the transit system
23	Who is responsible (entity) for the stray current corrosion control, maintenance, testing and monitoring?	Engineering and Track Maintenance Department	Engineering and Track Maintenance Department along with the help of corrosion consultant	Engineering and Track Maintenance Department	Transit agency is responsible once the problem is reported
24	Do neighboring utilities currently believe they are experiencing transit caused stray current effects?	Yes, however, things are under control	Yes, however, things are under control	Yes, however, things are under control	Yes, however, things are under control
25	When was the first stray current corrosion related problem noticed? When was it repaired?	Don't know the initial occurrence but, hand rails on the high bars corroded	No problems found. Track slab rebar system is very efficient in keeping the stray current contained as designed.	Don't have any program. Now dealing with the problems as they arise. Utilities started the testing and complained about Stray current on their lines	Visually found during the track survey, don't remember the date - ongoing issue has been the failure of lead cable.
26	What measures were taken to control and/or remove the stray current corrosion issues?	Used Steel handrails and replaced the concrete in which the hand rails were embedded	Regular testing informs transit agency about any problems - Testing done every 3 years	Testing and maintenance work is in process on some select lines	Lead cables were replaced
27	How long the repairs have been going on?	Regular maintenance repairs are carried out on need basis	Regular maintenance repairs are carried out on need basis	N/A	It's an ongoing task, depending on complains
28	Is historical corrosion and repair data available? Can it be reviewed?	Confidential	Not available	Not available	No
29	Is there a log of maintenance conducted to address the stray current corrosion?	No	No	No	No

S. No.	Question	Transit Agency 1	Transit Agency 2	Transit Agency 3	Transit Agency 4
	<b>Transit Agency Name</b>				
30	Is there a log of total cost of the corrosion repairs to-date? Can it be reviewed?	No	No	No	No
31	Currently, are there any stray current corrosion problems?	Yes	No	Yes	Yes
32	Have stray current corrosion issues caused to modify the maintenance plan or stray current control methodology? Can the plan be reviewed?	Yes	No	No	N/A
33	Has the present stray current corrosion problem been repaired/fixed?	Yes (E-clips replacement project)	Corrosion consultant is currently conducting the survey and will address the issue if any	Corrosion consultant is currently conducting the survey and addressing the issues.	Yes
	<b>Cost</b>				
34	What was the total cost for the most recent stray current corrosion repair?	Don't have that detail (the E-clips replacement project was \$600K)	Don't know - Corrosion consultant performs the repair work if required	Corrosion consultant has been hired to access the magnitude of repair work required	Don't know
35	How many stray current corrosion repairs are typically made per year?	Don't know	N/A	N/A	Don't know
36	Has the frequency of stray current corrosion related problems decreased or increased with time?	With the mitigation of current issues we are expecting the corrosion to decrease	No change	The problem accumulated for the last many years and are surfacing now. In general the frequency has increased	The frequency has decreased however, being an older system issues come up on regular basis
37	How many route miles of light or heavy rail are currently under construction and/or planned over the next few years?	Don't know	10+ miles of LRT	Don't know	Don't know
38	For in-progress transit construction and/or planned extensions over the next few years (if any), what stray current control provisions are expected and/or engaged?	All new construction to follow the guidance provided in the transit agency design criteria manual	Isolating pads under rails and fasteners, rail on top of concrete slab, cross bonding, and track slab rebar system	Isolating pads under rails and fasteners, rail on top of concrete slab or ties, Sacrificial anodes, and cross bonding	Structure stray current drainage, Ungrounded negative return circuit, rail isolation, utility relocation and protection

S. No.	Question				
		Transit Agency 1	Transit Agency 2	Transit Agency 3	Transit Agency 4
39	What is the latest total annual operating cost for the rail system?	\$30 million (maintenance and operation)	Confidential Information	Confidential Information	Confidential Information
40	What part of the total operating cost is for non-vehicle maintenance?	\$5 million	Confidential Information	Confidential Information	Confidential Information
41	What is the estimated annual cost for stray current corrosion repairs excluding the consultant fee?	\$0 (the cost is covered through additional grant money)	Don't know	Don't know, this will be the first year	Confidential Information
42	What do you estimate the repair costs due to stray current corrosion to be for the next 5 years?	Don't know	Don't know	Don't know	Don't know
43	What percentage of this cost will be the consultant fee?		~\$250K for periodic maintenance and testing	Don't know	Don't know
44	Is there a certain budget to address the on-going stray current corrosion issues?		No	Didn't have any program so there was no budget.	No
45	Is the transit system still in need of any repair/mitigation to control the stray current issues?	Yes	The only recurring cost is the regular testing and maintenance conducted by the consultant	Yes	Yes
<b>Summary</b>					
46	“Lessons learned” from the stray current corrosion incidents and/or repairs?	Regular inspections and testing is necessary to avoid major failures.	Do not embed the track and if embedded ensure that rail is well insulated and is on dedicated ROW	Regular inspections and testing is necessary to avoid major failures.	Maintenance plan, Guidance and Standards needed, man power, funding for the repairs.
47	What changes or modifications other than above lessons learned would you like to see or recommend to the industry?	National Standards and Guidance manuals	Guidance and Standards needed to maintain the tracks	Maintenance plan, Guidance and Standards needed to maintain the tracks	

S. No.	Question				
	Transit Agency Name	Transit Agency 1	Transit Agency 2	Transit Agency 3	Transit Agency 4
48	Is there a local electrolysis committee to discuss stray current issues?	Yes	Yes	Yes	Yes
49	Do you participate in the local committee?	Yes	No	Yes	Yes
50	What stray current design specifications or manuals have been the most helpful in the past? Which ones have guided your design and maintenance methodology?	Transit agency design criteria	NACE and IEEE standards	NACE and IEEE standards	Transit agency design criteria
51	Do any Federal guidelines impact your design and maintenance approaches? Are there any that have a negative impact?	No	No	No	No

S. No.	Response from Transit Agencies				
	Transit Agency 5	Transit Agency 6	Transit Agency 7	Transit Agency 8	Transit Agency 9
1					
2	Design criteria includes provisions for switch heaters	Hot and foggy climates, wider track gauge	Snow and ice conditions, so we use hot air blowers, pan heaters, cal-rod heaters, and 3rd rail deicing cables powered by our dc traction power. No concrete in these areas.	During winter there are periods below the freezing point and therefore de-icing salt is applied to roadways and point heating units are installed.	Coastal environment, different conditions in autumn and winter.
3	31 - Years (In service since 1986 with various new routes since then)	45 - Years (In service since 1972 with various new routes since then)	59 - Years (with various new routes since then)	20 - Years (with various routes since then)	10 - Years (with various routes since then)
4	60 miles of LRT	110 miles of LRT (double track)	189 miles of LRT, 42 miles of HRT	43 miles of LRT	20 miles of LRT (double track)
5	115RE, Ri59/13, and Ri52	AREMA 119RE	Subway: 100ARA-A (old) and 115RE (new and replacement rail). Street car: 115lb head hardened	Ballasted sections: 113lb, Raised or slab track construction: 80lb, Embedded rail: Corus rail 59R2 type coated rail / Corus Rail 35GP rail	Standard 54EI (previously named UIC54)
6	Total = 52	Total = 62	Total = 66 (including street car stations)	Total = 30	Total = 19
7	< 1 mile	> 1 but < 2 miles (with few longer sections)	> 1 but < 2 miles	> 1 but < 2 miles (with one longer than 2 mile section)	> 1 but < 2 miles
8	Slightly > 1 mile	slightly > 2.2 miles	< 2 miles (slightly > 5.5 miles on Streetcar)	slightly > 2.7 miles	slightly < 2 miles
9	No correlation	0 to up to .43 miles	Some are on same location whereas others vary	Most substations are close to stops	Same location

S. No.	Response from Transit Agencies				
	Transit Agency 5	Transit Agency 6	Transit Agency 7	Transit Agency 8	Transit Agency 9
10	Track isolation testing includes rail boot holiday test, rail-to-earth and rail-to-rail resistance testing. Also, pipe-to-earth potential measurements are taken on selected underground utilities that cross, or are adjacent to the ROW. On elevated structures, baseline rail-to-rebar, rail-to-earth, and rebar to-earth potential measurements, and collector mat to earth current measurements are taken.	Not Sure	The standard is to have baseline stray current studies done prior to and after a subway line is in service. No baseline testing was done on the older lines. Only track-to-earth resistance testing is conducted as part of maintenance testing	During construction rail-to-earth resistance values are recorded. Monitoring is undertaken at selected locations on third party utility assets at risk of stray current corrosion. Monitoring includes logging of corrosion potential of the asset and current flow in accessible bonding straps.	The conductance per unit length is calculated as the length of the track section is known.
11	ASTM: C0876, D257-91, and G165. NACE: RP0104, RP0169, RP0188, RP0274, RP0572, TM0497, and TR35201. ASM Handbook, volume 13C. NACE: Peabody's and Cathodic Protection Survey Procedures	Transit agency design standard	None are listed in the baseline surveys. For the track-to-earth resistance tests, transit agency standard is 250 ohm/km.	EN 50122-2, EN 50162, Office of the Rail Regulator Tramway Technical Guidance Note No. 3 – Stray Current Design	EN 50122-1, -2 and -3, European Standard, Railway applications- Fixed installations – Electrical safety, earthing and return circuit: Part1, Part2, Part3
12	200 ohms/1000 track feet - Embedded track 500 ohms/1000 track feet - DF and Ballasted track	500 ohms/1000 track feet	.01 ohms/km to an average of 36 ohm/km. varies for different lines	Between 5 to 20 ohm-km (single rail)	As per EN 50122-2, conductance per unit length for a single track is 0.5 S/km
13	Track-to-earth measurements are not part of regular scheduled maintenance.	N/A	.02 ohms/km to an average of 27 ohm/km. varies for different lines	20 ohm km (single rail) - only where the construction value met or exceeded this	As per EN 50122-2 the recommended conductance per unit length for a single track is 0.5 S/km
14	Rail isolation; including rail boot, bath tub construction for turnouts. For DF and ballasted tracks use of insulating pads and fasteners. Use of HDPE instead of ductile iron, casings, IJS, anode beds, impressed current, and test stations for utilities	Insulated rail pads, Negative grounding devices, Substation spacing. Cross bonding	Insulated pads, rail clips, impedance bonds, cross bonding to name a few	Minimize leakage at source by maintaining a high level of rail to earth resistance and low return circuit resistance; this is combined with a stray current collection system in the street running sections to collect a high proportion of any current that does leak.	Isolated track constructions, short distances between substations, dimension of return cables to ensure low resistance to the rectifiers, return rails to have a sufficient cross section to lower the resistance of the return path.

S. No.	Response from Transit Agencies				
	Transit Agency 5	Transit Agency 6	Transit Agency 7	Transit Agency 8	Transit Agency 9
15	Structure stray current drainage, Ungrounded negative return circuit, Yard TP isolation from main line, insulated rail fasteners, shop TP electric isolation from yard	Electrically isolated yard, Insulated rail fasteners, Structure stray current drainage, Ungrounded negative return circuit, Diode grounded negative return circuit, Electrically bonded reinforced concrete structures	Ungrounded negative return circuit – LRT only. Streetcar lines are grounded. Electrically bonded reinforced concrete structures	Diode grounded negative return circuit, Insulated rail fasteners, Structure SC drainage (SC mat), Utility SC drainage, Electrically bonded reinforced concrete structures, Yard TP electrically isolated from mainline	Ungrounded negative return circuit, insulated rail fasteners, electrically bonded reinforced concrete structures, isolated yard TP, utility SC drainage isolated from metro structure earth
16	Yes, visual inspections are conducted	Yes. Ongoing continuous rail replacement program	Yes - Ongoing rehabilitation project replaces track rails, plates, clips, ties, and ballast that have exceeded the limits specified in maintenance standards.	Yes - includes; track cleanliness, Ballast maintenance, and check on diode performance, bonding, and line insulation	Visual inspections are carried out every other month
17	Yes; continuous monitoring on two lines. The rest of the system will be included in coming years.	No, unless a stray current problem is suspected or reported	Yes every 3 to 4 years	Yes, typically every few years (Footprint test). In the past substation monitoring several times each year	A voltage limiting device connected between return rail and structure earth includes an voltage transmitter which is used to analyze if changes in the normal behavior is detected. This is performed on a monthly basis
18	No	No	Yes - including detailed procedures	A test plan is prepared when undertaking the Footprint test which includes running a single tram around the network whilst monitoring at traction substations and utility assets	A written procedure is elaborated by the company in charge of the operation and maintenance of the metro. Confidential document
19	No	No	The testing is only for track-to-earth resistance	Not routinely but a measurement was included in a recent Footprint test	Yes
20	Not being measured	unknown	The testing procedure breaks down the lines in sections	Only limited data during construction – areas of embedded rail with less than the 5 ohm km are desired.	

S. No.	Response from Transit Agencies				
	Transit Agency 5	Transit Agency 6	Transit Agency 7	Transit Agency 8	Transit Agency 9
21	Yes	No	Yes	No - generally corrosion is identified and therefore no detailed investigations are undertaken	Yes
22	Yes - Receive notification from the owner of the utility	Yes; Arcing, pitting, flaking of metallic components	Yes	During embedded rail replacement corrosion of the rail was observed.	No
23	Engineering Department	The engineering and the maintenance department	Engineering and Track Maintenance Department	Electrical Maintenance Department	The O&M contractor has the obligation to maintain the system including stray current corrosion as well as corrosion due to other circumstances (environmental issues)
24	Utilities will notify the agency if testing on their equipment indicates TP related SC problems	Yes, however, things are under control	Yes, and they have reported problems that have not yet been addressed	Yes, however, things are under control	Things are under control
25	April 2005 (report provided)	Don't know	From the records, in 1974 there was an issue with public utilities and stray currents.	Stray current interference has been measured and investigated since start of operations	An issue regarding water in the tunnel that was not drained sufficiently was noticed during operation and mitigated
26	Mentioned in report	Rail pad replacements, additional rail insulators, additional cross bonding	A procedure was set up then to install blocking diodes, which is still the standard today for surface feeding substations	Where SC interference is high (i.e. failing criteria) investigations are undertaken, and the issue is rectified to reduce SC	A program to improve the drainage slope at few locations along the tunnel was set up and mitigation was performed
27	Repairs have been completed	30+ years	Repairs are always ongoing	N/A	
28	No	No	Not available	Not readily available	New System
29	No	No	No	No	Yes

S. No.	Response from Transit Agencies				
	Transit Agency 5	Transit Agency 6	Transit Agency 7	Transit Agency 8	Transit Agency 9
30	No	No	No	No	No
31	No	Yes	Yes	No identified locations	No
32	No	No	Stray current issues have modified the track maintenance plan to include for better isolation of negative rail.	Stray current management is documented in the Engineering Reports for the transit agency	No
33	Not yet, repair work to occur next year(s)	No	Yes - Currently looked into	N/A	N/A
34	\$75k	Don't know	Cannot break out costs.	N/A	N/A
35	Less than 1	Don't know	On average 5-6 per year.	Embedded rail was replaced	N/A
36	No change	Increased	It has increased recently due to the age of the original equipment reaching the end of their lifecycle.	Detailed historical data is not readily available to allow frequency of interference issues to be determined	N/A
37	7.3 miles of LRT	15 miles of double track HRT	HRT miles 8.6 km, Streetcar miles 19.1 km		15 km of double track LRT
38	Structure stray current drainage, Ungrounded negative return circuit, electrically bonded reinforced concrete structures, rail isolation, utility relocation and protection	Ungrounded negative return circuit, Electrically bonded reinforced concrete structures, Structure stray current drainage, Utility stray current drainage, Cross bonding	Isolating pads under rails and fasteners, rail on top of concrete slab or ties Utility stray current drainage	Ungrounded negative return circuit, electrically bonded reinforced concrete structures	Ungrounded negative return circuit, electrically bonded reinforced concrete structures

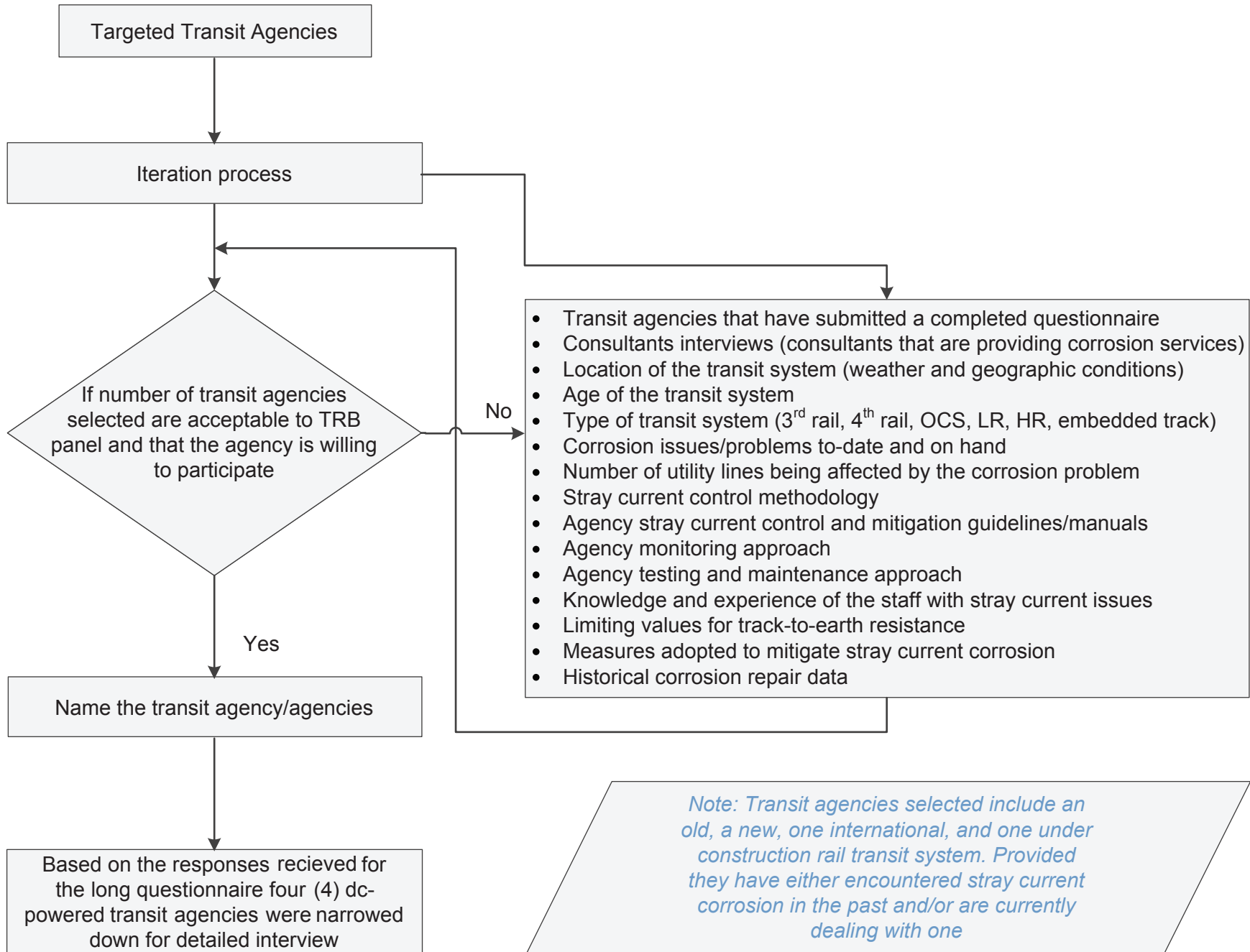
S. No.	Response from Transit Agencies				
	Transit Agency 5	Transit Agency 6	Transit Agency 7	Transit Agency 8	Transit Agency 9
39	Total budget for operation, maintenance-of-way, and vehicle maintenance is \$50 million	\$540 Million	2011 Operating budget - approx. \$1.6 billion.	Confidential Information	Confidential Information
40	MOW budget is roughly \$15 million	Don't know	Not available	Confidential Information	Confidential Information
41	\$25k budget amount for rail isolation	Don't know	\$600,000 (recent). This does not include Track Maintenance work.	No cost	Confidential Information
42	\$25k budget amount for rail isolation	Don't know	5 X 600,000 = ~ \$3.0 million	No cost	
43	No consultant fee expected	Don't know	~ 4%	N/A	
44	See response to 41	No	See response to 41	No	
45	Yes, see above answers	Yes	Yes.	The stray current collector cable on a section has been stolen and is awaiting replacement.	No
46	All parties involved need to be educated on the requirements and importance of SC control and proper mitigation installation. Design criteria and technical specifications must include corrosion control	None	The hollow rail boots used for sound and vibration purposes are not good for electrolysis mitigation. Water gets trapped between the boot and the rail, the hollow boots are full of water, and the breaks in the boots have all contributed to much faster electrolysis corrosion of the rails at the breaks in the boots.	It is recognized that the insulation of embedded rail in shared ROW is a challenge. Tests during construction should be undertaken to assist in finding any faults at an early stage.	Include a surveillance system that informs of changes compared to normal conditions (surveillance of the voltage between return rail and structural earth)
47	None	None	All utilities need to have an understanding of the issue and have personnel who can deal with it.		

S. No.	Response from Transit Agencies				
	Transit Agency 5	Transit Agency 6	Transit Agency 7	Transit Agency 8	Transit Agency 9
48	No	No	Yes - there is a society for controlling Electrolysis that includes utility companies to discuss the electrolysis issues.	Yes	
49	None available	No	Yes, we meet once per year and are in contact with the representatives as issues and projects arise.	Yes	
50	NACE specifications have been the most helpful. Ongoing design methodology influenced by lessons learned, filed measurements, collaboration with utility personnel.	None	The Consultants have used NACE and IEEE Std. 81, and the agency has its own design standards.	Office of the Rail Regulator Tramway Technical Guidance Note No. 3 – Stray Current Design	The VDV recommendations and the EN standards. The laboratory for Corrosion Protection and Electrotechnology
51	No	No	No Federal guidelines exist.	Guidance taken from EN 50122-2	No negative impact but the state railway has some requirements for other transportation system operations in the vicinity of their systems that are a challenge to fulfill.



## APPENDIX E

# Decision Tree



*Note: Transit agencies selected include an old, a new, one international, and one under construction rail transit system. Provided they have either encountered stray current corrosion in the past and/or are currently dealing with one*

*Abbreviations and acronyms used without definitions in TRB publications:*

A4A	Airlines for America
AAAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI-NA	Airports Council International-North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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