A UNIFORM SYSTEM FOR STRAY CURRENT ISOLATION AND QUALITY CONTROL

Thesis

submitted by

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DECLARATION

I, Saud Arif Memon, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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ABSTRACT

Stray current leakage and the resulting corrosion has been a source of concern for Direct Current (dc) transit agencies and utility companies since the inception of electrified rail transit systems. Stray-current leakage is more significant in dc-operated transit systems, in areas of low soil resistivity and where the rail is embedded. These tracks typically run through urban traffic areas, city centres, tunnels, and between utility lines that require the rail to be continuously isolated to provide adequate track-to-earth resistance.

The aim of this research is to develop a framework of guidelines to isolate, mitigate and/or eliminate stray current corrosion. The thesis uses data collected from transit agencies and corrosion consultant interviews, questionnaires, and field testing. This thesis recommends a progressive process of stray current control starting with base line surveys of dc transit systems. It then recommends early coordination with the utility owners, and mandates regular maintenance and testing of the transit system.

A uniform system for rail track isolation supplemented by quality control testing and maintenance guidelines will not only help to reduce stray current corrosion faced by dc transit agencies but will also reduce the increasing cost of corrosion repairs.

This research reviews and documents the advancement of computer modelling techniques and improves on previous simulation models used to calculate maximum rail potential, stray current potential, and total stray current. The developed simulation model includes the calculation of potential metal loss on the neighbouring third party infrastructure, which was absent from previous models. The model considers a floating system and was applied to obtain total stray current leakage on real life dc transit system projects commissioned to consultants from around the world.

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Finally, I would like to dedicate this work to my late father who inspired me to believe in myself enough to even take the first step to initiate this thesis.

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Acronyms

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
BART	Bay Area Rapid Transit
BRT	Bus Rapid Transit
BSI	British Standards Institute
CDEGS	Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis
COH	City of Houston
CP	Cathodic Protection
CTA	Chicago Transit Authority
dc	Direct Current
DDOT	District Department of Transportation
FEM	Finite Element Method
FHWA	Federal Highway Administration
GCRTA	Greater Cleveland Regional Transit Authority
GPS	Global Positioning System
HCC	Houston Community College
HRT	Heavy Rail Transit
HVDC	High Voltage Direct Current
ICRE	International Conference on Railway Engineering
IEEE	Institute of Electrical and Electronics Engineers
IET	Institution of Engineering and Technology
ISBN	International Standard Book Number
JRC	Joint Rail Conference
LA	Los Angeles
LA-METRO	Los Angeles Metropolitan Transportation Authority
LRT	Light Rail Transit
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
NAS	National Academies of Science
NASA	National Aeronautics and Space Administration
NCTRP	National Cooperative Transit Research and Development Program
NY	New York
NY MTA	New York Metropolitan Transit Authority
NYCT	New York City Transit

OCS	Overhead Catenary System
QC	Quality Control
ROW	Right of Way
RPCD	Rail Potential Control Devices
RTD	Denver RTD
SCC	Stray Current Control
SEPTA	Southeastern Pennsylvania Transportation Authority
STD	Standard
TCRP	Transit Cooperative Research Program
TF	Track Feet
TMC	Texas Medical Center
TPS	Traction Power Substations
TRB	Transportation Research Board
TTC	Transportation Technology Center
UFC	Unified Facilities Criteria
UMTADC	U.S Department of Transportation and Urban Mass Transportation Administration
US	United States
UTA	Utah Transit Authority
UTA TRAX	Utah Transit Authority
WMATA	Washington Metro

Nomenclature

Symbol	Description	Unit
M	Mass of metal loss	grams
I_{coor}	Corrosion current density	A/m^2
F	Faraday's constant (96,490)	C/mole
n	number of electrons	_ -
r	leakage resistance between track and earth per unit length	Ohms per m
Ω	Track-to-earth Resistance and/or rail to earth resistance	Ohms per 300m
δ	resistance of track per unit length of line	Ohms per m
V	Track-to-Earth Potential	Voltage
I	Stray current	Ampere (A) & mA/m
H_z	Frequency	Hertz
ρ	Soil Resistivity	Ohm-cm
R	Rail resistance	ohm/km
G	Nodal Conductance	1/ohm
d	Utility diameter	d
D	Density of steel	g/cm^3
SC_d	Allowable current density	$\mu A/m^2$

1 Introduction

1.1 Stray Current in Electrified Rail Transit

Stray Current and the resulting corrosion has been a cause of concern among transit agencies, electrolysis committees, utility owners, providers, and electric railway carriers in the United States (US) and globally. With initial principles and mitigation methods dating back to the early 1900's, the first preliminary report on Stray Current Control (SCC) and mitigation in the US was prepared in 1916. The document was published as a progress report, after the end of the First World War, in 1921 [1]. Most of the principles identified and mitigation measures recommended in this 1921 electrolysis report are still adopted by the transit service providers today.

Stray current leakage and the ensuing corrosion is more of an issue in low resistivity soils and embedded tracks. Embedded tracks typically run through major traffic areas, city centers and treads 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 since the entire rail does not require continuous isolation from earth and separation is generally only required at the insulated contact points.

The engineering and transit community have a consensus that due to the lack of proper maintenance, testing guidelines and limited technical knowledge of the responsible staff, the industry approach to address stray current issues is more responsive rather than pre-emptive. There are some modern transit systems that have developed design and maintenance criteria documents addressing the limiting values for the control and collection of stray current. However, the maintenance, periodic testing, and quality control (QC) of stray current still remains an issue, particularly in the US, as does the introduction of standardized methods of rail isolation to mitigate and collect stray currents [3].

A uniform system for rail track isolation supplemented by QC testing and maintenance guidelines would not only help to reduce stray current corrosion but will also lessen the ever-rising cost of corrosion repairs to Direct Current (dc) rail transit system. Much of this repair cost is associated with the restorations performed either to the dc rail transit itself or to the neighbouring infrastructure elements including utilities [4, 5]. The absence of national SCC/mitigation standards or guideline in the US, necessitates the need for more research in this area. This research proposes contemporary standards and guiding principles to match the advancements made in other sectors of the rail transit system.

1.2 Scope – An Overview

Testing strategies coupled with mitigation and collection techniques, reduce stray current corrosion and related maintenance. Many transit agencies in the US, to this date, struggle to find uniform guidelines, state of the art standards for mitigation, testing procedures, and operational maintenance for stray current leakage. The transit industry needs a well-documented selection of mitigation methods along with maintenance and management plans tailored to different types of transit services.

The aim of this research is to develop a framework of consolidated guidelines and recommendations to mitigate stray current leakage from embedded tracks. To this end, the research uses data collected from transit agency and corrosion consultant interviews, field testing, and documents the advancement of computer modelling. Real case studies on stray current issues, commissioned by Houston METRO, and other transit agencies were used to facilitate the modelling process and real-life scenarios including but not limited to:

- Stray current analysis for a European transit agency.
- Analysis of stray current corrosion and damage to neighbouring utilities from the operation of Houston METRO Light rail transit (LRT), Los Angeles METRO, New York City Transit, Manchester Tram (Metrolink), Salt Lake City Utah rail transit, and Sao Paulo Metro Line.
- National and international transit agency corrosion issues and testing programs.

Part of the work described in this thesis (chapter 3 through 5) will contribute towards the development of a guidebook on the design of stray current control methods for dc rail transit systems in North America for the National Academies of Science (NAS) in conjunction with the US Transportation Research Board (TRB). This guidebook will be accessible for the use by transit agency design and maintenance practitioners, and will influence new system construction, extensions, and maintenance and operation of existing systems. Both Phase I and Phase II of the research for the aforementioned guidebook has been completed and approved by TRB and the publication of the guidebook is underway.

1.3 Contents of the Thesis

This thesis documents the effectiveness of stray current mitigation practices adopted by current national (US) and international transit agencies. For the purpose of this thesis, more focus is given to stray currents associated with embedded tracks, related mitigation methods, and the stray current limiting values.

This thesis is divided into eight chapters. The literature review section (Chapter 2) gives a brief outline of the process of corrosion, and the different traction power alternatives available to transit agencies. This section explains previous work on the control and mitigation of stray current corrosion including the calculations, based on available scientific papers and reports. It also includes the review of national and international design criterions/standards, and historical methodologies used for the control of stray current control where applicable. It encompasses the review of theoretical, practical as well as experimental approaches to address the stray current leakage and the ensuing corrosion issue in dc powered transit system. Some of the papers, standards, and reports studied include calculations for limiting stray current leakage using various mitigation methods and stray current modelling techniques.

Chapter 3 discusses the TRB research and the stray current control and collection systems at different actual dc powered rail transit agencies including their testing methods, operation modes, physical environment, and track construction type. The data for this discussion was assembled by communicating with the respective transit agency representatives and by studying their performance and maintenance standards. Information on some of these agencies is presented in this chapter.

Chapter 4 focuses on maintenance plans, testing procedures, baseline surveys, and actual testing at transit agencies. This section elaborates on the various stray current testing procedures and their results for an existing transit system and for a new transit system in the US. These test results were then used to compare the transit agency's observance of their stray corrosion criteria during regular operation and maintenance.

Chapter 5 provides a synopsis of the stray current issue and the best way to predict its effects. In this chapter a stepwise process is developed for achieving uniform stray current isolation and QC for an embedded track. The process is developed using data collected from literature research, coupled with the interviews from 30 US and international transit agencies, interviews and meetings with corrosion consultants, and stray current testing observations.

Chapter 6 explains the basic modelling principle and calculation of stray current leakage in a dc transit system. This chapter highlights the impact of corrosion on the utility structures in the vicinity, and the ensuing metal loss. Parameters like cross bonding, rail-to-earth resistance, rail resistivity, collection mat, and substation spacing, and their effects on stray current are explained using the proposed simulation model.

Chapter 7 contains the analysis of the results of stray current leakage and its effect on an actual dc transit system using the stray current simulation model developed. The modelling techniques presented establish both static and dynamic modeling to overcome the limitations of the existing simulation models. The results of the stray current model present the risk of corrosion on conductors near dc rail system.

Chapter 8 includes the review of work done, conclusions drawn, objectives achieved, and describes potential future work.

2 Literature Review

A literature review has been conducted to understand stray current, the process of its evolution, the associated corrosion, and the mitigation methods from the early days of the electrified rail systems, to the present-day design. Detailed synopsis of the historical development of the stray current mitigation is presented using calculations to explain specific methodologies adapted during specific eras. Some of these methodologies are still used today to control stray current in a dc transit system. The intent is to gain an insight and understanding of the physical principles and scientific significance behind the development of stray current control and mitigation methods adapted to date by rail transit agencies.

The literature and articles reviewed date back to 1916 [6] and cover a wide range of national and international findings on this topic. This research includes the study of technical journals, conference papers, books, and the review of significant related articles and reports by research institutes/agencies and/or organizations. The list of various agencies, whose studies and reports were reviewed for this research, includes but is not limited to, TRB, the Transportation Technology Center (TTC), the Transit Cooperative Research Program (TCRP), the American Public Transportation Association (APTA), the American Railway Engineering and Maintenance-of-way Association (AREMA), Unified Facilities Criteria (UFC), and Australian and European Standards. European and IEEE standards. The corrosion control criteria documents from various national transit agencies were also studied to develop a platform for comparative analysis and standard comparison. Some of the reports, in particular TCRP reports, gave an insight to a wide wealth of unparalleled history and background information on track related research [7], rail base corrosion detection and prevention [8], and LRT design [9].

In the US, the Corrosion Society distributed recommendations on stray current mitigation methods in 1916, followed by a published report in 1921 [1]. This report included some detailed mitigation techniques and construction recommendations. These techniques and methods were based on the study of the transit systems functionality 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 1910 – 1912)
- France – Regulations by Minister of Public Works (1911)
- England – British Board of Trade Regulations (1894 – 1912)

After reviewing recommendations from the above-mentioned countries and the research conducted by the local transit agencies in the US, the corrosion society suggested that further testing and guidelines were warranted. However, nothing substantial was done until the 1950s and then the 1960's when the sensitivity of the stray current topic increased again [4]. This was followed by another period in the 1980s and 1990s when the National Aeronautics and Space Administration (NASA) Technology Utilization and Industry Affairs Division conducted a research project for the US Department of Transportation – Urban Mass Transportation Administration and produced a manual on corrosion control; "A Corrosion Control Manual For Rail Rapid Transit by Gilbert, Lloyd, Fitzgerald" [10] and the first reference book by the name of "The past, present, and future of Rail Transit Systems" was authored by Szeliga [11]. This reference book presents a compilation of more than 30 technical papers on the stray current corrosion until 1994.

The literature review conducted for this thesis provides a synopsis of the technical methods used to control stray current over the years and the recent advancements in stray current control that have been made nationally and internationally. The literature review has shown that stray current is not as significant of an issue in alternating current (ac) traction power as it is in dc powered traction systems [12], yet both traction power systems are discussed briefly. The following subsections summarize the various concepts and topics.

2.1 Corrosion and Corrosion Rate

Corrosion is 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; air, water or soil. The practical definition is the tendency of the metal to lapse back to its natural state [13]. In simple terms corrosion is a natural chemical reaction between a metal and its surroundings where the metal is oxidized (loses electrons), resulting in its progressive degradation. The corrosion tendency varies for different metals due to the energy content of the elements in their metallic state and is highly dependent on the surrounding environment.

The process of corrosion typically requires four elements; electrolyte, anode, cathode, and a metallic path. Oxidization (loss of electrons) takes place at the anode forming ions. 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. An 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 reduction reaction. However, at least one such reaction must take place at the anodic surface for corrosion to take place making it compulsory 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 [14].

The following equations represent a typical anode and cathode reaction. Oxidation occurs when current leaves the rail to earth (anode reaction) and reduction occurs when the current returns to the rail (cathode reaction):

$$M \rightarrow M^{++} + 2e^{-} \text{ (Oxidation at Anode)} \quad (1)$$

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \text{ (Reduction at Cathode)} \quad (2)$$

Where *M = element involved (steel)*

e = electron(s), O = oxygen, and H =hydrogen

For corrosion to take place both reactions need to occur at the same time. The level of corrosion is typically measured by checking if the damage is caused by uniform attack or localized attack. In uniform attack, the mass of metal corroded per unit of the surface area will define the damage. For localized attack, also referred to as pitting corrosion, the depth of penetration on a metal will define the corrosion rate [13]. Corrosion rate is a function of many variables and thus in most cases it cannot be calculated without making some assumptions. However, Faraday's law is used to define the amount of reduction that occurs in an electrolytic cell [15].

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

Where, I_{corr} = corrosion current density in A/m^2

F = Faraday's constant 96,490 *C/mole (Coulombs per mole of electrons)*

n = number of electrons transferred per molecule of a metal corroded.

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, yet the metal loss is much faster due to the large amount of stray current leakage [15]. The potentially large electric current leakage, depending on its potential source, makes stray current more aggressive than galvanic corrosion. Thus the potential damage by stray current corrosion can be many times greater than that by galvanic corrosion.

To put it into perspective theoretical loss caused by one ampere of dc current that is constantly flowing from a metallic structure for one year will result in the dissolution of 9kg of iron, 34kg of lead, 10kg of copper, and 3kg of aluminium [3].

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

It is essential to understand the cause of corrosion to help determine the most effective guidelines, principles and inspection techniques for corrosion mitigation. There are many forms of corrosion depending on the type of metal, the surrounding environment, and the length of exposure to the environment. This thesis focuses only on the types of corrosion caused by stray current from dc powered transit systems.

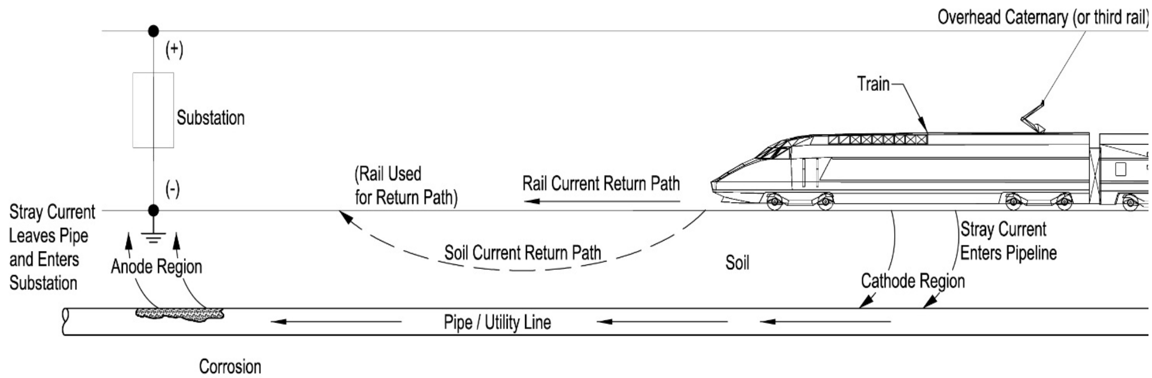


Figure 1: Stray Current Corrosion Path

2.2 Stray Current & 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 that rail has a finite resistance, the return current leaks in to the earth and find 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, electrically isolated from the running rails and the surrounding soil. This fourth rail collects the current and returns them 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 1). This causes significant 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 flow of the current into the conductor earth.

Though dc electrified transit systems are the main cause of stray current, there is another form of stray current called Telluric Current. This is caused by transient geomagnetic activity [13]. The Telluric Current's influence on structures is for a limited duration due to non-localized discharge areas and thus is rare to find. Currents caused by other systems and operations are not discussed further in this thesis and the focus is on stray currents caused by the dc transit system.

Stray current affects all the metallic components that are under the track including the reinforcement steel supporting the neighbouring structures and the 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. To reduce the 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 [9].

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) and the properties of the metal. Figure 2 is a simple circuit model demonstrating the basic components affecting the levels of stray currents generated by a dc traction power system [17].

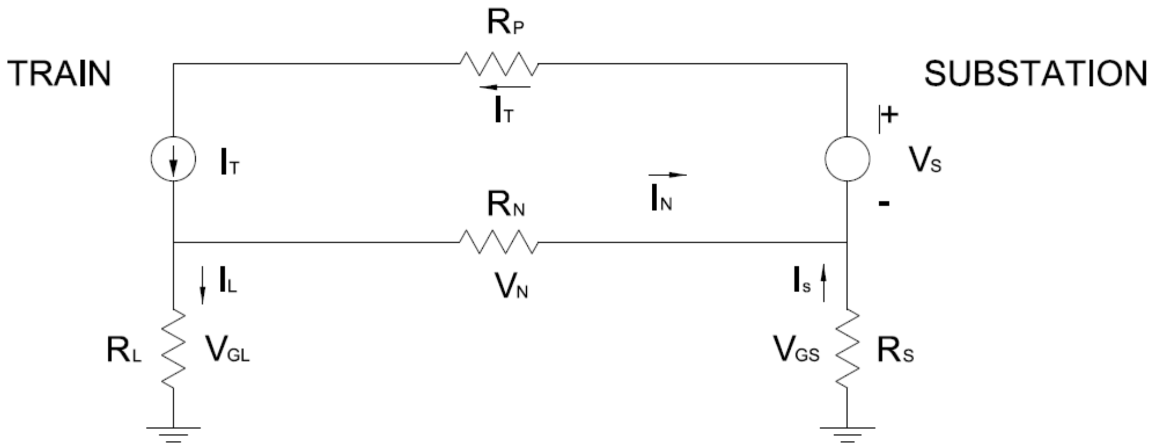


Figure 2: Simple Circuit Model illustrating Stray Current Components [17]

R_N = Resistance of Negative Return Circuit

R_P = Resistance of Positive Circuit

R_L = Track-To-Earth Resistance at the Load End

R_S = Track-To-Earth Resistance at the Source End

I_T = Train Operating Current

I_N = Current Return through the Rails

I_L = Leakage Current to Earth at the Load End

I_S = Current Returning to Substation through Earth

V_S = Substation Voltage

V_{GL}= Track-To-Earth Voltage at the Load End

V_{GS} = Track-To-Earth Voltage at the Substation Location

V_N= Voltage Developed across R_N by I_N

The relationship between the voltages V_N, V_{GL}, and V_{GS} are presented by the equations below:

Where: $$V_{GL} \approx \frac{R_L}{R_{L+}R_S} \times V_N \qquad (5)$$

$$V_{GS} \approx \frac{R_S}{R_{L+}R_S} \times V_N \qquad (6)$$

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

The corrosion rate is directly proportional to stray current and is more severe when it is focused on a small area. However, unlike natural corrosion, stray current corrosion is independent of oxygen concentration and pH level of soil and is mainly related to the dc currents from the rail transit [18]. Although generally referred to as electrolysis, it is the process where chemical changes take place in the electrolyte when direct current flows through a metal [12]. The entire process of corrosion of the underground metals is accelerated by stray current. The rail-based corrosion gets worst (expedites) due to electrolysis caused by dc at the contact point with wet debris (mud, slime) build up under the rail base and due to de-icing salts [8].

Stray current not only corrodes neighbouring utilities, but also affects the metallic structure of the transit system itself. Based on a report prepared and provided by NACE, Battelle Memorial Institute, and the U.S Department of Commerce, in 1990, the cost of corrosion caused by stray current was estimated to be $500 million annually [19]. This number primarily accounts for the losses to the dc powered transit agencies and detrimental effects to the surrounding infrastructure and utilities. It does not take into account the costs associated with signal problems. A recent study supported by TRB in 2007, on the "rail base corrosion detection and prevention", suggests that steel used in the fabrication of the 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 [8]. Table 1 shows estimated average stray current leakage by a transit system.

Table 1: Estimated Stray Current Leakage (in Amps) by a Transit System [20]

Track-to-Earth Potential (V)	Track-to-Earth Resistance (ohms - Ω) per 300m of Track (2-Rails)						
	10	25	100	250	500	1000	12500
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

2.3 Traction Power

Transmission of electric power has always been along the track by means of an overhead wire (Figure 1) or at ground level by means of a third rail laid on the ground (extra rail) close to the running rails. AC systems use overhead wires whereas dc can use either an overhead wire or a third rail. 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. With economics and cost being the deciding factor in the selection of the train circuit return path, running rails have been used in most of the rail transit systems as the return conductor for the return of the traction power to substation. The running rails are at earth potential and in some cases are directly connected to the substation.

Since the inception of the electric traction there has been debate on which supply system is better. Though the scope of this thesis is not to determine the respective advantages of dc and ac transit systems, it is important to understand the basic variation between the two systems. The general rule is that ac systems are used for longer distance commuter and high-speed rails, due to its higher reliability and reduced maintenance requirements, whereas dc traction is used for shorter distances like metro and suburban lines. In the early days, the ac powered vehicle had to carry a transformer onboard to convert high voltage to a lower system voltage. These transformers were heavy and for smaller trains, carrying a limited number of passenger, it was inefficient in terms of weight per vehicle to have them on board. However, the introduction of ac motors around 1965 eliminated the need for converting ac current to dc [21].

For dc trains the transformer is located at the substations, along with the rectifier, to supply dc power. This increases the efficiency of the vehicle, representing a balanced weight/cost vs. passenger capacity for short distances, and makes it reliable with lower equipment failures. Globally, over half of all electric traction systems still use direct current [21]. However, based on the literature reviewed for this thesis, and owing to the advancement in traction power, ac traction power is the preferred option in countries building new rail systems. This includes high-speed lines primarily due to the much higher reliability and reduced maintenance requirements of ac traction motors [21]. A High Voltage Direct Current (HVDC) transmission system has been used for economy and power flow control, but it is yet to be used for a rail transit system.

Some of the most commonly used and proven traction systems presently used by the transit industry are:

- dc 600V, 750V, 1500V and 3000V overhead catenary
- dc 600Vand 750V third rail
- ac 16.7Hz 15000V and 50Hz 25000V overhead catenary

Based on the literature review, Table 2 below illustrates some of the common advantages and disadvantages of both the power systems.

Table 2: Comparison of Traction Power Systems (based on literature research).

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: • delivers power over longer distances • allows for less frequent substations	Delivers traction power at low voltage which; • allows for tighter clearance • require more frequent substations
Ease of Maintenance	

Though this study is primarily focused on stray corrosion damage caused by dc systems, leakages of ac at industrial facilities have also been suspected to corrode buried metallic structures.

2.4 Dc Traction System Grounding (Earthing)

DC traction power design includes three different earthing systems, the solidly bonded or grounded systems, the floating or ungrounded systems, and the diode-bonded systems. Older transit system used solidly grounded earthing, but literature research shows that it caused more problems than it solved [2] details of which are explained in section 2.4.1. Floating, automatic grounding systems, and diode-bonded systems then emerged to satisfy the conflicting requirements of stray current and touch potentials. In a dc traction system, 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 is essential to reduce stray current leakage.

To have a clear understanding of the subject, it is important to first realize the difference between "equipment" grounding and "system" grounding. System grounding refers to grounding of the current conductors of the dc negative return system. Equipment grounding refers to the grounding of the enclosures of the rectifier unit and dc switch gear. Though equipment grounding is not within the scope of this research, it is important to know that grounding of equipment is recommended to ground the dc equipment enclosure rectifiers, and metal-enclosed dc switchgear [22].

The main objective of the system grounding for all transit systems is to offer the continuity of a safe power supply. This includes protecting human beings from an electric shock in the vicinity of the earthed installation and minimizing dc stray current during normal and fault conditions. To achieve this objective, the following grounding methods along with their limitations are used by the transit agencies.

2.4.1 Grounded/Solidly Bonded System

A grounded system is characterized by the direct metallic connection of the rectifier negative bus to the local ground grid at the substation. The absence of insulation on the running rails is an optional characteristic. This system permits the unregulated flow of current where stray currents will leave the running rails along the entire length and return at the substation ground grid using paths other than the rails. This leakage of stray current increases the potential of corrosion and thus this system is not used in modern dc transit systems [22].

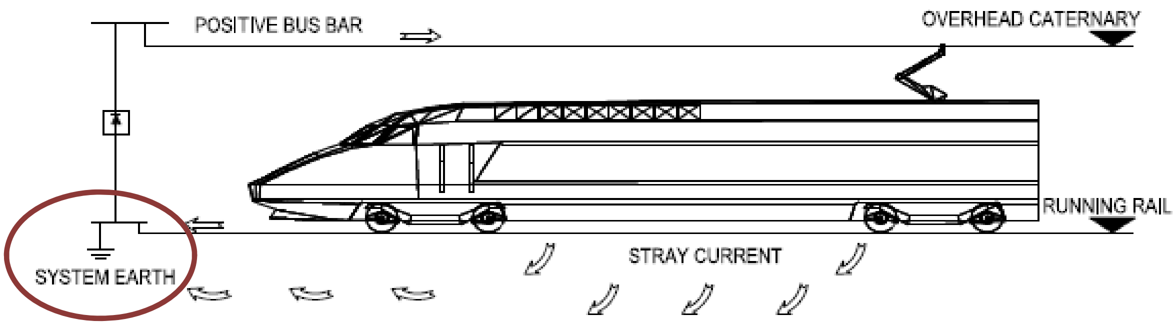


Figure 3: Grounded / Solidly Bonded System

2.4.2 Ungrounded or Floating System

Unlike grounded systems, the floating system has no deliberate connection to earth and thus represents the other extreme of the traction power design. Stray current is restricted by high rail-to-earth resistance using rail boot, rail coating, and rail fasteners. This could result in increased running rail voltage, as compared to the grounded system, causing safety concerns for public and the transit agency staff. Additionally, 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. The concerns are addressed with the use of overvoltage protection equipment and platform insulation procedures [22].

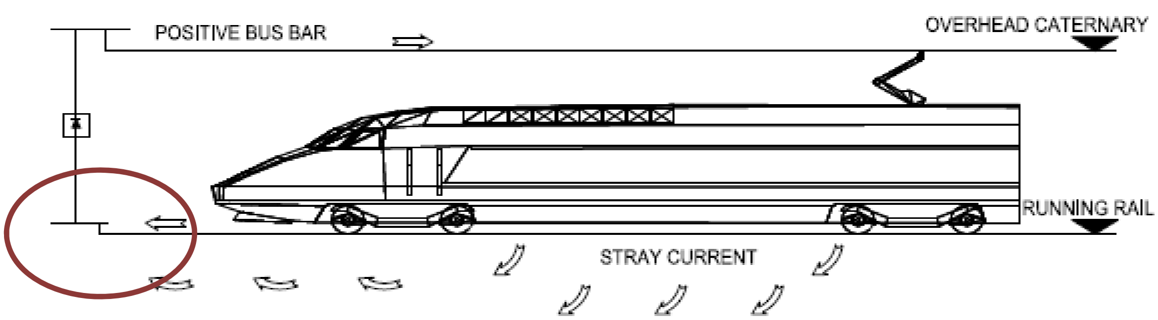


Figure 4: Ungrounded / Floating System

2.4.3 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 system and is generally 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 return of the fault currents. This also permits stray 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. 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 [23].

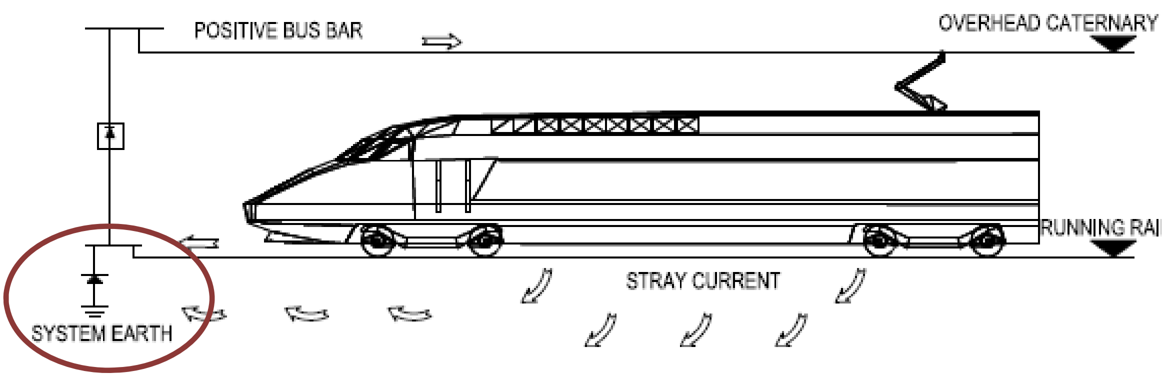


Figure 5: Diode Bonded System

2.4.4 Additional Research on System Grounding

A Study by Yu in 1998 [24] uses a simulation model to examine the merits of an ungrounded system in combination with rail potential control devices (RPCD) generally referred to as a Thyristor System (this is explained in detail further below). Different case studies were carried out to calculate the effective system design, keeping both rail potential and stray current in control. Based on the findings it is the author's opinion that a floating earthing system with RPCD's is the best choice for the transit system being designed. A later study by Soylemez et al in 2006 [25] validates the previous approach by Yu. The author recommends that RPCDs can provide an efficient mechanism to control the touch potentials, provided that they are set up properly. A study presented in 1998 by Bahra et al [26] addresses the principles of stray current control in the context of the grounding and bonding strategy for a dc railway system. This study highlights the advantages and disadvantages of the bonded and floating systems as well as their difference in stray current level by conducting a comparison of the two systems. Another study presented by Paul in 2002 [22], provides an account of dc traction power system grounding practices in North America. The paper first highlights the difference between equipment and system grounding and then discusses the stray current leakage and personal safety affected by various system grounding techniques. In additional to the three system grounding schemes described above, the author also presented the "Automatic grounding switch" and "Thyristor grounding" schemes. Figure 6 represents all the grounding schemes presented in the paper.

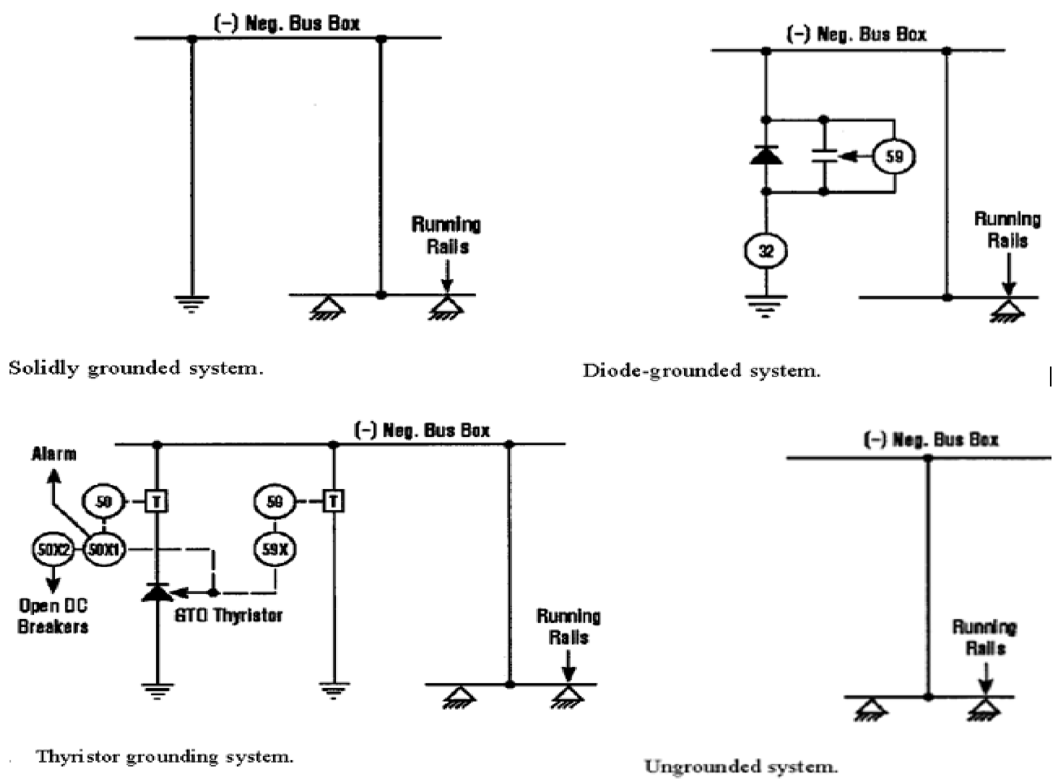


Figure 6: Grounding Systems Types [22]

The Thyristor grounding system will work as an ungrounded system under normal system operation and will earth the system only when an unsafe voltage (as per traction load design) occurs due to either train bunching load currents or due to positive (third rail)-to-earth faults. This gives the Thyristor system an edge over diode grounded system where diodes are always conductive (grounded system) under normal system operation and for small magnitudes of voltage between rail and earth. A study by Cotton et al in 2005 [27] also presents the impacts of different grounding schemes. The study, with the help of a simulation model, demonstrates the advantages of a floating rail system. It concludes that the total stray current leaking from a floating system can be “four times” less than that in a grounded system. The authors also highlight the facts that steps must be taken to maintain safe levels of rail-to-earth voltages during fault conditions for the floating system.

Two papers on the Taipei transit system by Lee et al, in 2006 [28] and in 2009 [29] carried out detailed analyses of the grounding schemes and their effects on rail potential and stray currents. Simulation models were used to analyse one of the tracks. They conclude that in general ungrounded systems generate less stray currents than diode grounded systems, whereas diode grounded systems are used to eliminate the stray current corrosion issues in old grounded systems. A more recent study presented in 2010 by Tzeng et al [30] highlights the results of a field test conducted on Taipei transit system’s Blue line to analyse the effects of rail potential and stray currents. The results of this field investigation further corroborate that a diode grounded system has more issues with rail potential and stray current than the ungrounded system.

Another study presented in 2011 by Alamuti et al [23] conducts a review of various earthing schemes and presents the corrosive effect of stray current control. The various earthing schemes include grounded, ungrounded, diode-grounded, and thyristor grounded. The simulation model is used to calculate the rail potential based on changing rail positions along the track for different schemes. Based on the results of the simulation model, they conclude that stray current corrosion is significantly higher near the traction power substation in comparison to other locations along the rail. A unique scheme was presented by Liu et al in 2005 [31], where the output voltage of the traction power substation is kept constant in a diode grounded system, thus reducing the stray current and rail potential. The author endorses the results with the use of a simulation model and demonstrates reduced stray current and rail potential values in this unique system as compared to the conventional diode grounded system.

Based on the findings of the research, it can be safely concluded that to date an optimal earthing setup that would decrease the stray current level and maintain touch potentials within 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 system varies for different systems. Typical examples are two scientific papers presented by engineers of Railway Systems Consultants Ltd, [32], and of Balfour Beatty Rail Projects Limited [33]. Both studies conclude that the grounding schemes will have to be case specific and tailored to each application and dominant conditions. This is another area where the transit agencies need specific standards and guidelines to design traction power systems. However, this is beyond the scope of this thesis. The author is part of the IEEE working group in the US which is working on developing and compiling the guidelines for dc traction power system and equipment grounding.

2.5 Soil Resistance – Corrosion and Earth Conduction

Another mitigation method for 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 prevents the stray currents from entering the soil and causing corrosion in the surrounding area.

Soil resistivity is used to gauge the degree of corrosion in underground utility lines. The literature review reveals 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 [14]. In comparison to other conductors like copper and steel, earth is a poor conductor of electricity. However, it changes to a good conductor when the area of the path of the current is large which in turn lowers earth's resistance due to the chemical composition of the earth. Generally, the resistance of the surrounding earth will 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 the soil changes with the type of soil, it is difficult to give an exact value of the soil resistivity and it is defined in a wide range of values. The amount of moisture content, soil content, and chemical constitution drastically affects soils resistivity [34]. A significant contributing factor to the variation of chlorines and sulphates in soils are the de-icing salts used on tracks. 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) [8]. An increase in temperature can decrease the resistivity of soil whereas the resistivity can increase as the temperatures fall below freezing. These seasonal variations make it difficult to assume a fixed value for earth resistivity and in order to establish the correct resistivity values, measurements are required.

Table 3: Soil Resistivity Range [34].

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*
Inorganic Clays of high plasticity	1,000 – 5,500*

*these results are highly influenced by the presence of moisture.

Table 4: Corrosivity Ratings Based on Soil Resistivity [8].

Soil Resistivity, Ohm-cm (Range)	Corrosivity Rating**
> 20,000	Essentially noncorrosive
10,000–20,000	Mildly corrosive
5000–10,000	Moderately corrosive
3000–5000	Corrosive
1000–3000	Highly corrosive
< 1000	Extremely corrosive

**Particularly to Chlorine and Sulphates

Resistivity of the soil is a significant factor in determining the most effective and efficient stray current collection system. Many elements factor into the resistivity of the soil, thus 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 using the soil resistivity levels. Theoretically, the resistance of any system of electrodes to earth can be calculated by the following expression [34]:

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

Where ρ is the resistivity of the earth in ohm-cm, L is the length of the conducting path, and A is the cross-sectional area of the path. Additionally, the Four-point method, also known as the "Wenner method", is the most commonly utilized method, depending on the depth, to determine the soil resistivity ($R = \rho/2\pi a$) [35].

A study by Pham, Thomas, and Stinger (presented at the 2001 IEEE/ASME joint rail conference), presented an earth potential gradient model that measures the potential developed between two points in the earth. The magnitude of this potential will have a direct link to the stray current effect on buried utilities. The earth potential gradient is calculated using the formula [17]:

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

Where: ρ = *Soil Resistivity, ohm-cm*

I = *current from source, amperes*

d_1 = *distance from source of structure*

d_2 = *distance from source of structure*

l = *length of current source (parallel rail), cm*

As acknowledged by the authors, Eq. 9 has the following limitations:

- Soil resistivity is assumed to be uniform within the length (*l*)
- Assumption that the earth potential gradients are not distorted due to the presence of pipes and are unchanged between any two points.

Using the earthing theory developed in the IEEE Standard 80-1986 [36], the same author has presented a method of calculating stray currents through earth. This spherical electrode model analyses stray currents from breakdowns in track insulation and is aimed to overcome the primary limitations of the earlier model.

A study presented by Dawalibi et al [37], on grounding systems in multilayer soils instigates the need to factor in the multilayer structure of soil instead of a uniform soil resistance for a safe grounding system design. The study presents various practical cases of earth touch potentials and touch voltages for different soil structures including frozen and low resistivity soils. A later study by Dawalibi et al, on the equivalence of uniform and two-layer soils to multilayer soils [38] concludes that conservative assumptions should be made to achieve a safe grounding system. It suggests performing earth potential measurements in a true multilayer soil structure in order to acquire the probable generated earth potentials and the resulting stray currents.

A study on the influence of soil structures on corrosion performance of dc transit systems was presented by Charalambous et al in 2007 [14]. The paper presents a simulation model to analyse uniform soil, two-layer horizontal soils and two-layer vertical soil resistivity. The study discusses how the stray current retained on the track bed is directly proportional to the soil resistivity, and the corrosion risk on the metal is inversely proportional to the soil resistivity. The simulation model concludes that low resistivity soil propagates severe corrosion. Therefore, the strategic placement of substations, factoring in soil resistivity, can help is controlling the intensity of corrosion. Another paper by Charalambous et al in 2008 [39] advances the earlier study and makes use of a simulation model to demonstrate the influence of soil resistivity on rail corrosion performance. The simulation model uses up to four vertical layers in the soil structure and further substantiates that low resistivity soils leads to increased corrosion.

Soil resistivity can be stabilized by chemical treatment during construction. Depending on soil type, chemicals like sodium chloride, magnesium sulphate, copper sulphate, and calcium chloride have been used to reduce soil resistivity by 15% to 90%. Chemical treatment is carried out on high resistivity soils to ensure an effective low resistance grounding system and/or stray collection system [34].

2.6 History of Stray Current Corrosion and Methods of Mitigation

Stray current corrosion has been a source of concern for transit authorities and utility companies since the inception of the electrified rail transit system. The corrosion problem was originally believed to be caused by a chemical mix of the soil. However, with time it was concluded that soil alone was not responsible for the extent of corrosion observed on the rail base and utilities and leakage of the traction current was noticed. In the US stray current corrosion was noticed in 1888 [40] in a dc powered rail line, in Richmond, Virginia. By that time Germany, France and England had also already observed the effects of rail corrosion caused by stray current. Older dc transit systems have more stray current issues due:

- 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
- Voltage of the traction power system

2.6.1 Historical Development

2.6.1.1 1890's to 1950's

Corrosion committees and the engineering community conducted numerous studies during this era on stray current problems and potential mitigation options. Those recommendations were implemented on the newer designs at that time with varying results including some adverse effects on the nearby utility lines, thus making it necessary to conduct further studies. In 1921, corrosion and engineering solutions were recommended by the corrosion committee to reduce the leakage and severity of stray current corrosion.

Following are some of the measures that were successfully developed to control stray current leakage and corrosion [1, 2]:

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

These four mitigation and control techniques are described in further detail below:

1) Bonded joints, cross bonding, and heavy rails

The use of heavy rail sections and suitably bonded rail joints were one of the earliest implemented mitigation methods for the control of stray current. The evolution of rail sections and steel, along with other metal compositions, has continued globally over the years. Rail sections have improved both in cross section, length, and the method of joining sections of rail. With joints being the weakest link in a track system, various methods of connecting the rail lengths have been explored over the years. This lead to the conclusion that welded joints provide conductivity equal to or greater than the continuous rail and are less subject to failure, with Thermit welds being 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 the embedded rails, within light rail transit systems. This resulted in the reduction of stray current and improved the performance of the rails. As time progressed, cross bonding between single track and parallel track rails was installed as an improvement to the welding to ensure rail connectivity and to equalize the current flow between the rails, thus reducing voltage drop (rail potential). In the US, cross bonding was placed at a distance of 150m on urban and 300 to 600 metres on suburban railways. In Germany cross bonds were provided at every 100m. In France they were placed every 50 to 100 metres and in England at every 36.6m [1].

2) Resistance to earth and insulation of negative return feeders

Resistance of the ground immediately in contact with the rail depends on the type of ground material. Measures were taken to insulate the track from the earth to reduce the stray current process. This resulted in reduced corrosion of the base of the rails and other grounded steel structures for embedded rails in urban areas. Maintenance of the tracks was also suggested by the corrosion committees to keep the vegetation out of the tracks; keeping the track 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, 4].

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 compared to concrete. Authorities in Germany and England were of the view that leakage of current cannot be reduced by the roadbed construction. In the U.S it was recognized that well drained crushed stone ballast had a resistance from 2Ω to 5Ω per 300m of single track. In comparison, the resistance of solid concrete ballast in contact with the rails and also earth roadbeds, was only from 0.5 to 1.5Ω per 300m of single track and 0.4Ω for 300m of double track. It was also established that the resistance in dry weather may be three or more times higher than for wet weather [1].

Insulated negative return feeders were widely used in the early construction, 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 insure the continuity of the return circuit. However, soon it was detected that these buried bare conductors increase the contact area between the return circuit and the earth, therefore counteracting the significance of their need [6]. It was also deduced that the use of frequent substations along the route provided more economical increase in the track current drainage points compared to the use of insulated negative feeders.

3) Maximum number of Traction Power Substations

Another stray current mitigation technique that saw more advancement 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. This results in the reduction of track voltage drop, thereby reducing the amount of stray current. Technology Papers by the Bureau of Standards on leakage of currents from electric railways, issued in 1916, by Stratton, M'Collum, and Logan [6] explain the importance of reducing the feeding distance to minimize the stray current leakage for both grounded and ungrounded systems using the following mathematic expressions. Logan et al made use of general equations for an isolated railway line to calculate the total leakage current, using the resistance of track per unit length, total current, and the leakage resistance between the tracks and ground.

$$i = A\, e^{\sqrt{\frac{\delta}{\gamma}}(x)} + B\, e^{-\sqrt{\frac{\delta}{\gamma}}(x)} \qquad (10)$$

$$i = A\, e^{ax} + B\, e^{-ax} \qquad (11)$$

Where: ($a = \sqrt{\frac{\delta}{r}}$ and A and B are the integration constants)

r = leakage resistance between tacks and remote earth per unit length of line

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

x = distance from outer end of line of any point under consideration

$\delta =$ *resistance of track per unit length of line*

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_oL. Thus, the total leakage current up to any point x can be calculated using the following equations.

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

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

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 $i_o = d_i/d_x$. Thus, the leakage current up to any point x can be calculated using the following equations.

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

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

Where:

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

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*

L = total length of line

Making use of the above equations stray current curves are defined in Figure 7. These curves show the effect of the feeding distance on stray current for a defined load of 40 Amperes per 300m, length of line 6000m, leakage resistance of 0.4Ω for 300m of double track, and track resistance of 0.004Ω/300m. The figure allows a 10% (percent) increase in the resistivity of the track to account for cross bonding. It 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 into half. It is also 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].

Maximum stray current for ungrounded system

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

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

Maximum stray current for grounded system

$$i_1(max) = i_o L(1 - \frac{\tanh(v)}{v}) \qquad (17)$$

$$Where\ \ v = aL$$

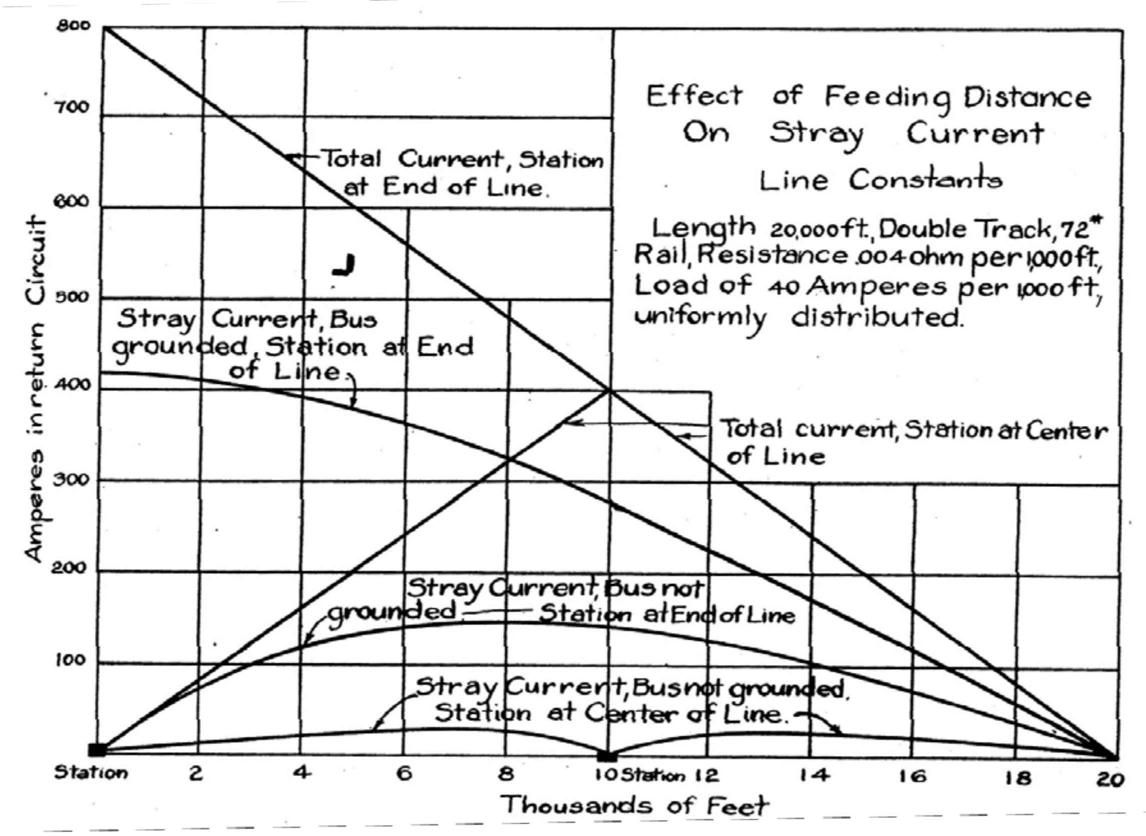


Figure 7: Effect of Substation Spacing on Stray Current [1]

Using the above equations potential gradient on the tracks and potential difference between earth and rails can be calculated.

Potential gradient and potential drop (respectively) for ungrounded system

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

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

Potential gradient and potential drop (respectively) for grounded system

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

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

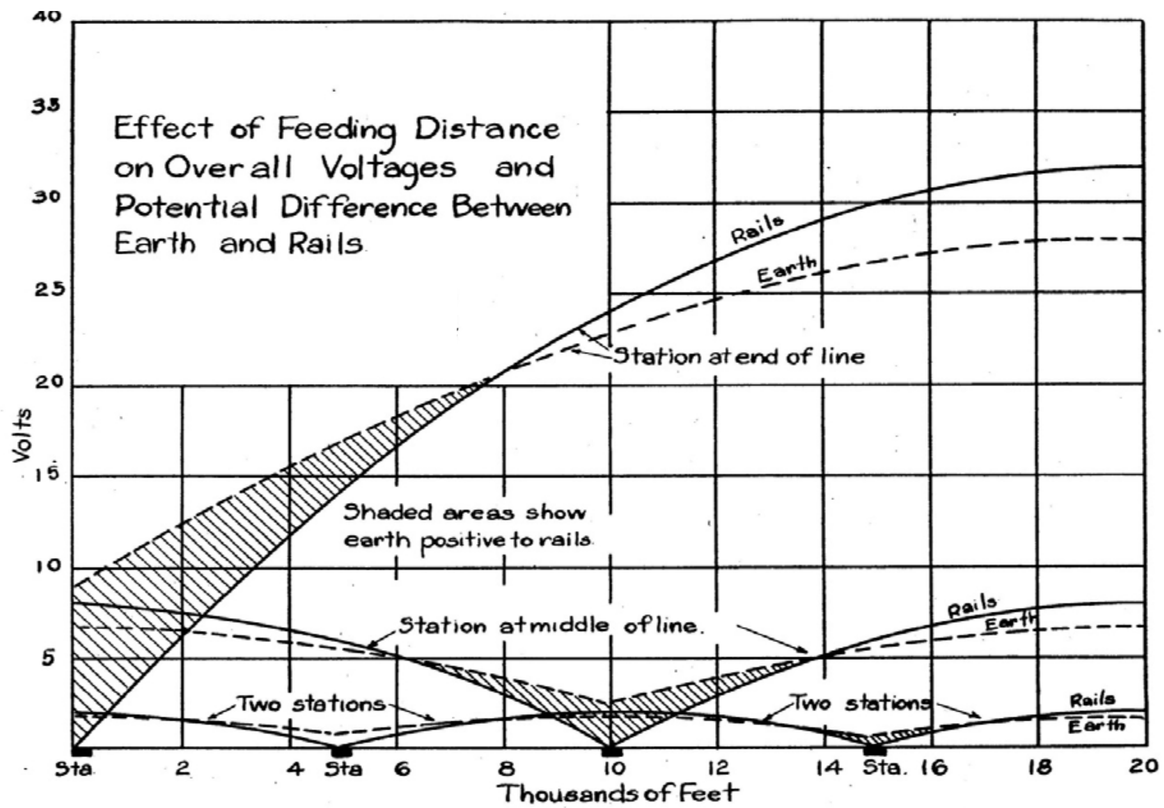


Figure 8: Effect of Substation Spacing on Voltage [1]

Figure 8 shows 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 above are based on a theoretical condition with no stray current whereas the actual curves will be lower since a portion of the current will leak to the earth [1]. It was observed by the electrolysis committees, as illustrated in Figure 8, that the overall voltage reduces by the square of the feeding distance when the feeding distance is shortened. 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 on this subject in the US. The initiation of automatic and semiautomatic controls for substations made it economically feasible to increase the number of feeding points. The average feeding distances in England were around 3 to 5km [1].

4) Three-Wire Traction Power System and other Methods

This method was similar to the city power system where one trolley is negative and the other 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 this method was not widely used by transit agencies.

Besides the adoption of the aforementioned methods to mitigate stray current leakage, the need to develop measures to protect utility structures from transit agency stray currents was also realized. The measures that emanated from the realization of this application included surface coating of pipes, use of conduits in cable construction, use of insulating joints, pipe drainage, interconnection of affected structures, and the rail return circuit [5]. Other measures included keeping new utility construction at a greater distance from the rail lines, avoiding the crossing of rail lines, and placing utilities as deep as possible in areas where utilities must cross the tracks [3].

Some of the methods proved effective, required more testing and development and were studied and investigated further. Other methods that were originally recommended by the corrosion committee in 1921, like the drainage bond mitigation technique, were widely criticized later by the engineering community due to the variation of conductivity for different types of pipes under different conditions, their material properties, and variety of joint types. It was further realized that drainage bonds necessitate costly periodic supervision and testing [5], and in certain cases would increase the overall stray current leakage [11].

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. In drainage bond diodes and reverse switches are used to mitigate stray current corrosion on affected structure. Insulated wires or cables are run from underground pipes or metallic structures to transfer the current from such structures to the substation [41]. This potentially reduces the flow of current from such structures to earth and other conductors. Three types of drainage bonds in use are:

1. Direct drainage bond; as the name suggests is a direct bond between the affected structure and the substation (or return circuit) and may include resistors.

2. Forced drainage bond; this includes a separate source of DC power to enhance the transfer of the stray current.

3. Unidirectional drainage bond; this type will include a diode to ensure that the current flows in one direction only.

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 very popular, they are still used by some transit agencies to avoid unsafe levels of track-to-earth voltages caused by stray current.

2.6.1.2 1960's to 1990's

Taking advantage of the studies and detailed investigations conducted in the earlier era, most of the transit agencies adopted recommendations that were made 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). Advancements were made in the areas of track-to-earth resistance, rail return circuit resistance, traction power substation 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 non-metallic pipes for new utility lines, making metallic pipelines electrically continuous, installation of testing locations along the new track construction, and maintenance solutions were jointly recommended by the rail transit agencies and utility companies. These solutions resulted in significant adjustments to rail transit systems, to control stray current leakage by decreasing the rail return circuit resistance and increasing the resistance of the rail-to-earth leakage path [4]. Decreasing the resistance of the rail return path was achieved by undertaking the following;

- Increasing the cross-sectional area or size of the rail; using standard size rails ranging from 40 to 55 kg (115 RE tee is the commonly used rail with a longitudinal resistance of around 40 – 80mΩ/km).
- Maintaining a continuous electrical path for the negative current by using continuously welded rails and welded cable bonds on special trackwork, and frequent cross bonding (every 150 to 300 metres).
- Decreasing the traction power substation spacing to 1.6 to 3.2km to reduce the voltage drop between the two substations.

Increasing the resistance of the rail-to-earth leakage path, which is also a useful approach to mitigate stray current leakage, was accomplished by undertaking the following measures [4]:

- 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 it has been observed that the rail life on diode-grounded transit system reduces to 20% of the actual life [11]
- Isolating the track in the yards and storage areas by isolating the sections of the main track [42].

The running rails were directly grounded and earthed back to the nearest substation via insulated cables to protect the staff from electrical shock in the yards and shops. This resulted in excess leakage of stray current since the only way back for the current to the substation was through the ground. 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 could only be applied to new transit systems (like grounding system, substation spacing, rail cross section etc.) others could be applied to old systems as well. Suggestions were made for a regular inspection, testing and maintenance program following severe weather changes, street and pavement repairs, and after the track and substation repair work to minimize the slippage of stray current leaks and avoid cost repercussions in the form of utility line corrosions. Failed installation and maintenance within a generally correct approach can also lead to stray current leakage. Figures 9 through 11 represent example mistakes that can occur during construction, installation, and operation like a poorly insulated fastener connection, broken rubber boot, a missing insulated fastener clip, and a rubber boot sleeve, respectively. The installation and maintenance mistakes in these figures were noticed during the stray corrosion testing conducted for this thesis on tracks under construction.

Figure 9: Cracked Insulation Cap on the Fastener Clip

Figure 10: Broken Rail Rubber Boot on the Rail Requiring Excavation

Figure 11: Missing Insulation at Clips and Missing Rail Boot Overlap

2.6.1.3 2000's to the Present

Design of earthing installations, substation spacing, track-to-earth resistance, and return circuits for dc transit system are currently the best reactive methods for controlling stray current and touch potentials. Learning from past experiences, most of the newer rail transit agencies have started designing their rail lines with provisions for control of stray current within the limits of their transit system by increasing the track-to-earth resistance. In the process, some transit agencies have also incorporated testing and maintenance plans in their design criteria documents. Tests like pipe-to-soil potential, track-to-earth resistance, track slab current measurements and 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 (rubber boot surrounding rail). 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 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 the stray current corrosion by using a combination of mitigation and collection techniques including, but not limited to, the use of elastomeric grout, insulated rail fasteners, embedding rail in troughs, providing current collection mats, and collector cables.

Though most of the mitigation methods and principles suggested by the corrosion committee originated from the 1920's are still in use, technical advancements have been made in the mitigation methods and new methods have been embraced by newer rail transit systems. The decision of when to use a method and/or a combination of methods, and what level of stray current corrosion protection is required continues to remain unclear for some of the rail transit providers. In spite of the 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 on innovative approaches like forcing the return current to return through a conductor wire instead of rail or earth [43]. Transit agencies have started adding their own test facilities for the collection of stray current data in addition to the utility company test facilities.

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

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 Resistance of the Earth-to-Rail- Leakage Path		
• Track-to-Earth Resistance	X	X
• Ungrounded Traction Power Substation	X	X
• Storage Yard / Mainline Isolation	X	X

Additionally, following are various other methods and/or techniques that are used standalone or in combination with each other to achieve stray current control [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/ballast contact by maintaining the ballast at a minimum of 2.54cm 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 trackwork
- 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 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) [44]
- Use of current collection mat and collector cable [45]
- Conducting regular testing of the transit system and nearby utilities
- Maintaining an on-going maintenance program that monitors rail-to-earth resistance values, keeps track-bed areas clean & well-drained.

There is an absence of standards and guidelines to select stray current mitigation measures for the US transit industry. The industry does have numerous stray current corrosion control methods to choose from but does not have clear direction on which one to pick, and which stage to pick it at. Mitigation measures are selected by the transit agencies retroactively based on the problem at hand rather than taking a proactive and/or all-inclusive approach at the inception of system design. The issue is further supplemented by the absence of a uniform design of isolation and lack of implementation of QC tests to confirm proper isolation.

Not all the methods can be implemented for every transit system and most of the design parameters like traction power, utility coatings, CP, substation spacing and train headways for the transit system are pretty much standardized, with the exception of track-to-earth resistance. CP in fact, has been a popular and most utilized mitigation technique by utility companies to address both the galvanic and stray current corrosion [46].

Research has been carried out on the resistivity of concrete in the presence of stray current. This research covers the corrosion behaviour of steel and steel fibres in concrete [18], corrosion damage of steel in concrete [47], and the corrosion rate of steel in concrete [48] in the presence of stray current. It is beyond the scope of this thesis to go in to the detailed analysis of the resistivity of concrete and the corrosion of steel in concrete. However, research shows that stray currents do induce corrosion in steel in the presence of chlorides [49]. The risk of corrosion on steel fibres (used for reinforcement) is low primarily because the electrical connection between the steel fibres (manufactured fibres composed of stainless steel) is unlikely for the volume ratio of steel fibres [50]. Research also shows that stray currents may accentuate the fatigue damage of reinforced concrete [51]. It was observed during the construction of a local dc street car project that high resistivity concrete presents construction challenges. These challenges include: special effort for finishing, early on shrinkage cracking of concrete, and extended curing times [52]. A study by Yang et al shows that stray current corrosion resistance of high resistive concrete with fly ash and powered slag is more than five times that of regular concrete with 100 year of concrete design service life [53].

2.7 Design Criteria and Standards

A review of the design criteria manuals of a cross section 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. None of the documents mention the origin and/or the basis of the limiting values for the return voltage or the stray current. In some cases, it is not clear if any initial baseline surveys were conducted by the transit agencies to justify these limiting values. Some transit agencies did not have a design criteria document or elected not to share their design criteria.

Table 6: Design Criteria Manuals for Transit Agencies

Reference	Transit Agency	Title	Latest Revision
[54]	Houston METRO	METRO Design Criteria Manual	April – 2007
[55]	Phoenix METRO	METRO Design Criteria Manual	January – 2007
[56]	Denver RTD	Design Guidelines & Criteria	November – 2005
[57]	New York City Transit Authority (NYCTA)	Corrosion Control Manual	June – 1984
[58]	Seattle, Sound Transit	Link, Design Criteria Manual	May – 2011
[59]	Utah Transit	UTA Design Criteria Manual	July – 2010
[60]	Portland, Oregon	Tri Met – Design Criteria	January – 2012
[61]	Washington DC	DC Streetcar Design Criteria	January – 2012

The above documents were either downloaded directly from the transit agencies website or were provided by the traction/corrosion department at the agency. There is an ASTM designation G 165 – 99, that was issued in 1999 as a standard practice for determining rail-to-earth resistance, yet it is not followed by many transit agencies [62].

To better understand what the international transit agencies are using for stray current control, the following English version European and Australian standards were reviewed as part of this thesis;

- BS EN 50162:2004 – BSI (British Standards Institution), Protection against corrosion by stray current from direct current systems [63].
- BS EN 50122-1:2011 – BSI, Railway applications – Fixed installations – Electrical safety, earthing and the return circuit. Part 1: Protective provisions against electric shock [64]. This standard specifies the protective provisions in fixed installations related to electrical safety in ac and dc traction system
- 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 D.C. traction systems [65]. This standard explicitly deals with stray currents resulting from dc traction power and is the most applicable standard to this research.
- BS 7430:2011 – Code of Practice for Protective Earthing of Electrical Installations; gives guidance on the methods that may be adopted to earth an electrical system for the purpose of limiting the potential [66]
- EP 12 30 00 01 SP – Electrolysis from Stray dc Current – RailCorp, Engineering Standard Electrical, Version 3.0 [67]
- SPG 0709 – Traction Return, Track Circuits and Bonding – RailCorp, Engineering Standard Electrical, Version 2.5 [68]
- APTA RT-S-FS-005-03 – Standard for Traction Electrification Stray Current Corrosion Control Equipment Inspection and Maintenance. APTA Volume 5 – Fixed Structures. Draft 2004 [69].
- NACE International, Task Group – 297, Direct Current Operated Rail Transit Stray Current Mitigation [70].

The above-mentioned standards specify appropriate stray current control measures that can be applied to dc systems along with some defence strategies against the effects of stray currents. However, these standards do not specify stray current control testing.

2.8 Study of Simulation Techniques

Computer based simulation models have been used for over two decades to calculate stray current leakage and its potential impact on dc rail transit systems and other neighbouring infrastructure. These simulation models are categorized as either static or dynamic. Conditions where the train load (current) is at a fixed point in time is referred to as static modelling. Where the train position varies as a function of distance and time, such simulation models are referred to as dynamic modelling. This section presents and evaluates the different modelling principles developed and used for the design of stray current leakage and highlights their capabilities and limitations.

A paper by Goodman et al in 1990 on modelling of rail potential rise and leakage current in dc rail transit system [71] presents a static model to calculate stray current. Assuming uniform rail parameters, the rail is treated as a transmission line excited by a finite current source energized at multiple points. However, in reality the parameters R (longitudinal resistance of the rail) and G (leakage conductance between the rail and the earth) will vary based on the number of rails for the return conductor, local soil, and ballast conditions respectively. Knowing that in reality it is difficult to achieve a close form solution for situations with varying parameters including multiple substations, and substation grounding conditions, Goodman developed a simulation model using a circuit model approach called “Finite cell modelling”.

As the name suggests, the transmission line is divided in to a number of longitudinal sections called finite cells. A simple ladder network of lumped elements (cells) is constructed with its varying R and G parameters and can be solved by nodal voltage equation as shown below.

$$[G][V] = [I_s] \qquad (22)$$

Where, *G= conductance, V= Voltage, and* I_s*= Injection current*

Accuracy of this model depends on the length of the line, number of cells used, and the end resistance. It is demonstrated that reasonably accurate results can be obtained if the finite cells are electrically "short" and the propagation effect is insignificant. This finite cell modelling approach is elaborated to represent many parallel conductors and forms the basis of a systematic approach to calculating stray currents.

Another study from Goodman et al in 1992 [72] describes two main parameters regarding the potential damage due to stray current. The parameters, total leakage current (stray current), and gross electrical charge leaked are then calculated with the help of a simulation model. Various test runs are carried out for both dry and wet conditions with and without the depot connection. Based on the results of the simulation the authors present a number of conclusions on the total stray current and rail potential. These include:

- Ungrounded scheme results in lowest total stray current whereas grounded scheme results in the highest total stray current.
- Connection of depot to the tracks results in higher leakage currents.
- Lower rail-to-earth resistance increases leakage current significantly.

Using the finite cell technique, Case in 1999 [33] developed a simulation model where the running rail is divided in to a series of short sections or cells as shown in Figure 12. Longitudinal resistance (δR_T) and resistance to earth (δR_E) of the track are representative of each cell. Resistance (R_C) represents the longitudinal resistance of the overhead catenary. Nodal analysis is used to calculate the nodal voltages which can then be used to calculate the current in all the track-to-earth resistance elements. Stray currents are calculated by adding up all currents flowing in to the earth.

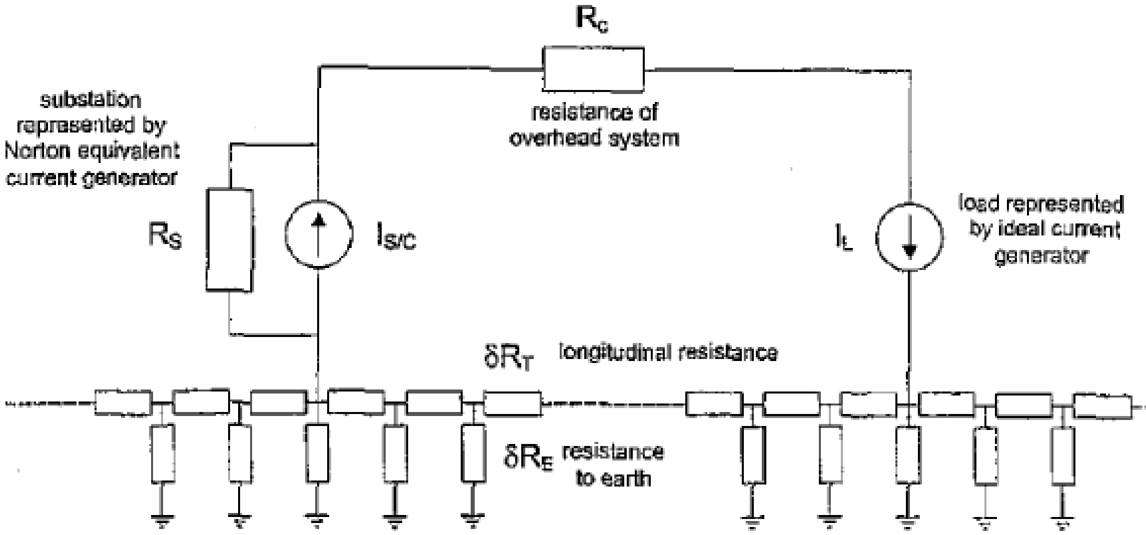


Figure 12: Equivalent Circuit Representation Using Track "Cells" [33]

Though Case's paper talks about the advantages and disadvantages of different grounding schemes and the author's grounding system preference, the model does not take into account various grounding schemes and only provides stray current level.

The nodal voltage analysis, a more complex simulation model, was developed by Cia et al [73, 74]. This multi-ladder dc circuit model uses lumped circuit components and is constructed to find circuit electrical solutions (Figure 13). The simulation model results include the rail potentials and total stray current of the system, along with branch node voltages and currents.

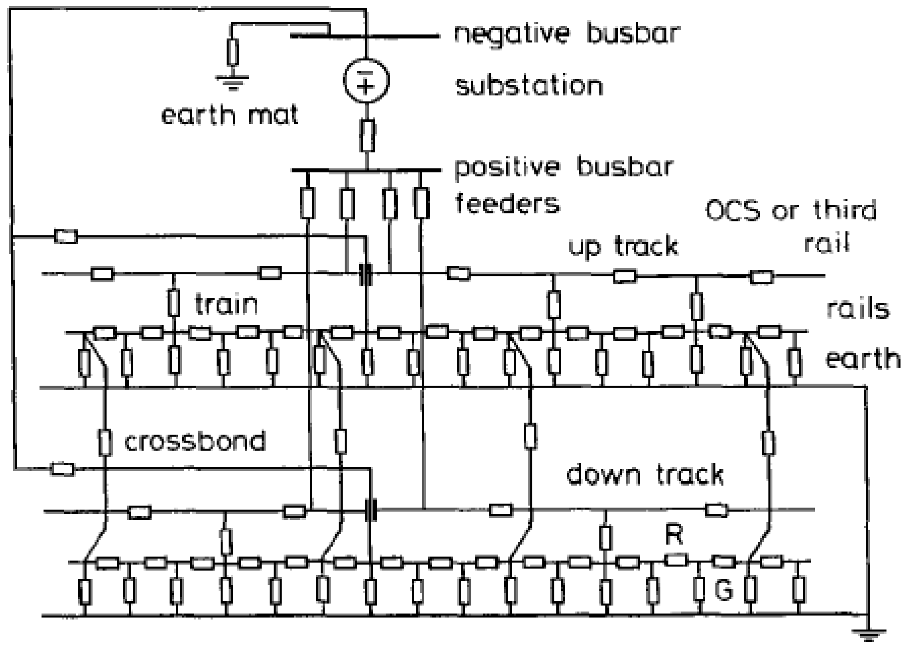


Figure 13: Multi-ladder network representation of double-track [73]

The electrical analysis of the simulation model is enhanced with the use of the Zollenkopf's bi-factorization method. The model does not account for the effect of the soil resistivity on the level of stray currents in utilities and is for static application only.

Another approach by Pham et al [17] assumes uniform soil conditions and uses a spherical ground electrode model to calculate stray current. Spherical electrode connections to earth (deliberate or unintentional) are used to model the negative return system. A basic stray current model using spherical electrodes is shown in Figure 14. Soil resistivity, effective size of electrode, and the potential to distant earth of each point are taken into account. This data is used to calculate the flow of current through earth from one grounded node, on the track of higher potential, to another grounded node on the track of a lower potential. This approach explores the relationship between utility grounding systems and the traction electrification negative return and when a current flow between them happens.

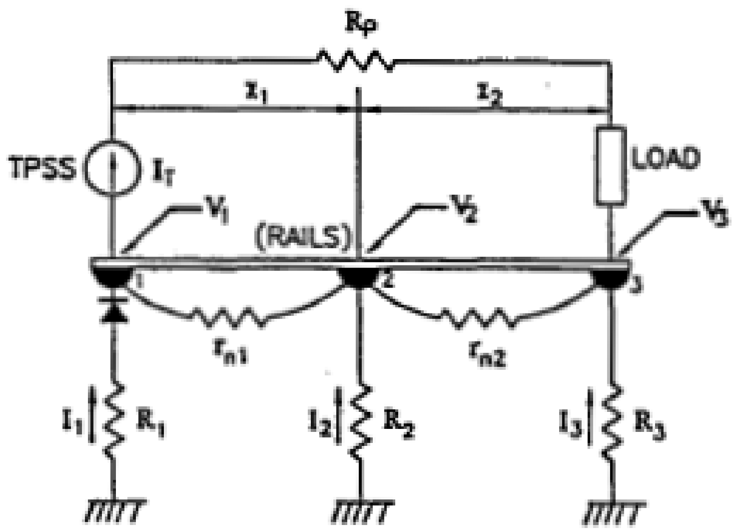


Figure 14: Basic Stray Current Model using Spherical Electrodes [17]

Another simulation model, “Stray”, was developed in 2003 by Ardizzon et al [75] to calculate stray current for traction systems at different conditions and included grounded metallic and reinforced concrete structures. The software model calculates the stray current leakage to earth and its value in different structures where there are other metallic structures at some generic distance from the track. This model is based on the matrix algorithm of equivalent electrical network, similar to previous simulation models.

The main hypotheses of the model presented by Ardizzon et al is that the earth (soil) is considered homogenous, the supply of traction power is known, and the absorbed current is considered independent of the voltage variations present in the contact line. For a reinforced concrete structure, the software assumes that the concrete is not carbonated nor polluted by chlorides. With this premise, the authors acknowledge that the study of the system is restricted to simple geometries with numerous exemplificative assumptions.

A series of studies on grounding strategy analysis and stray current leakage using simulation models are presented for the Tapei rail transit system from 2001 to 2010 [28-30, 76]. These simulation models vary from analysing the effect of various grounding strategies on stray current and rail potential to a broader analysis of rail potential and stray currents.

The most recent study [30] takes into consideration train performance characteristics, route data, operation parameters, and scheduled timetables. Performance characteristic data includes; weight and type of car set, speed and power consumption of each train-set, and gravity and curvature forces. Train operation parameters include the maximum acceleration speed, and maximum deceleration speed under normal and braking conditions. Currents flowing through each section of the negative circuit are computed using the steps described in the flow chart. The model takes into account the dynamic mode but applies to uniform soil only and requires some initial assumptions.

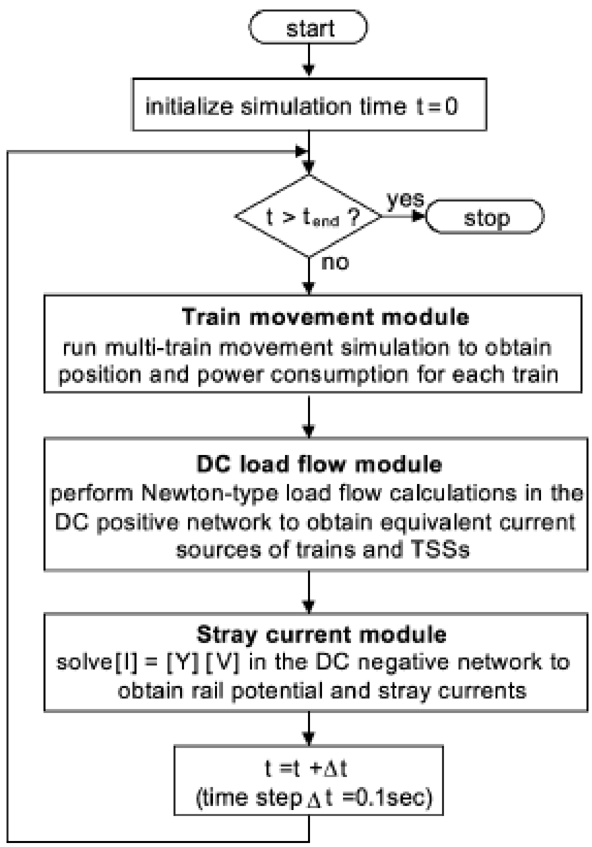


Figure 15: Computer simulation Flowchart for Stray Current [30]

Another series of studies by Charalambous et al [14, 27, 39, 77] presents a distinct approach using different soil resistivity structural models (uniform, horizontal and vertical-layer) to calculate stray currents. This model builds upon the previous work carried out on homogenous soils and compares results with CDEGS software [78]. The model uses the dynamic mode, where the train position and velocity vary as a function of time. It accounts for different soil models with varying soil resistivity to measure the stray current leakage. The results of this simulation model authenticate that non-uniform vertical soil along the route of a transit system can lead to a concentrated leakage current [27]. Using the same logic and approach, Charalambous et al developed a model to calculate the stray current effect on cut-and-cover tunnel sections of dc transit system [79].

The previous work is enhanced by the authors using a resistive network model (Figure 16) to compute the shunt and series parameters and to address the stray current distribution [39]. CDEGS, a commercially available software for calculating soil resistivity, is used to provide the data for the formation of the resistive network model.

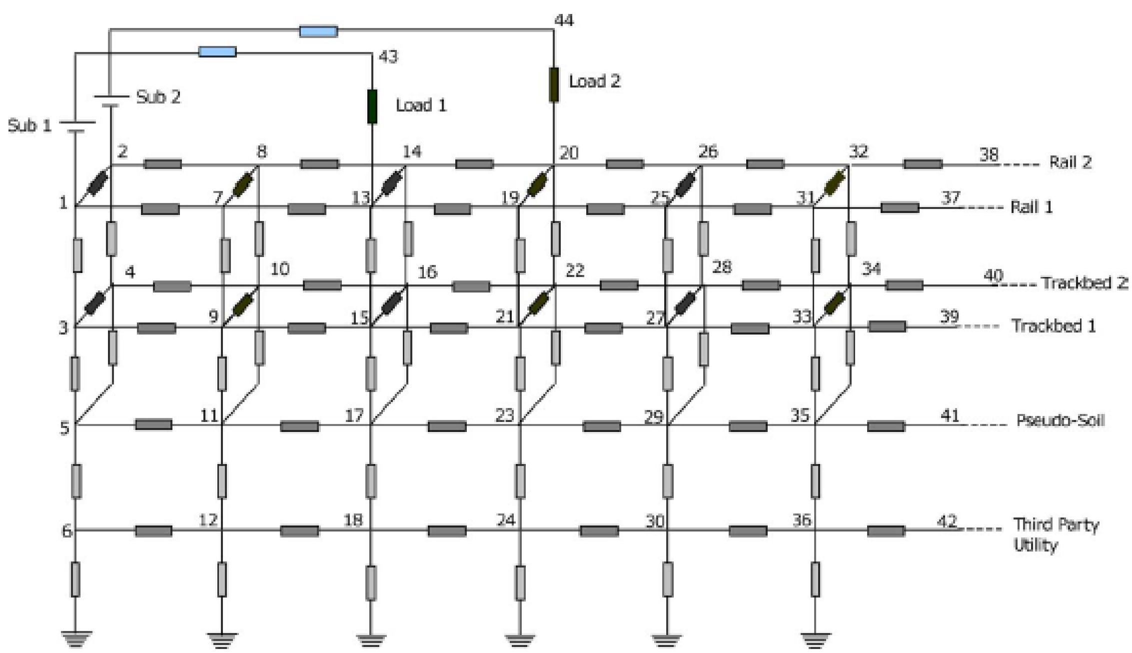


Figure 16: Resistive Type Network for the Double Track Floating System [39]

The main advantage of the software model over CDEGS is its ability to analyse simple case studies in less simulation run time. This model does not evaluate the metal loss and corrosion risk to any metallic infrastructure in the vicinity of the transit system.

A model has also been developed to calculate the remote effects of stray currents on rail voltages in dc transit systems [80]. This model uses gamma topology to calculate stray current, rail voltage, and voltage wave-fronts at any given distance along a track for a floating system. The software has been developed as part of the traction power software and thus calculates the real time parameters of the railroad at any given time. The author claims that the model is the most accurate method since it does not rely on the constant load and rather calculates the load current using power flow methods. However, the model assumes only a single train and uniform conditions like constant train speed and terrain slope.

In addition to the mathematical simulation modelling, Finite Element Method (FEM) analyses has been carried out on the subway tunnels to evaluate and mitigate the stray current effects caused by dc transit systems [81, 82]. The study proposes defensive measures to prevent the growth of anodic areas in reinforcement steel. The simulation results demonstrate that inclusion of equipotential connections between the steel of the adjacent segments will prevent the corrosion of the system.

Based on the review of the existing simulations, it can be established that some of them use a two-layer ladder circuit model instead of a single-layer transmission-line model. The distributed two-layer ladder model consists of the stray-current collector mat, stray-current collector cable, and provides the advantage of studying the efficiency of a stray-current collection system [83]. The single-layer transmission-line model does not have that advantage in evaluating the stray-current collection system efficiency. However, none of the simulation models evaluate the metal loss and corrosion risk of the metallic infrastructure in the vicinity and most models are based on assumptions and scenarios which cannot be directly applied to in a realistic dc powered transit system.

Stray current corrosion consultants interviewed, as part of this endeavour, indicate that they typically have their own Excel based in-house spreadsheet, in lieu of models, which calculate the leakage current once the train system design is completed.

2.9 Summary

With LRT systems typically operating on embedded tracks in city streets, stray current corrosion is a major concern to the track, utility and other infrastructure owners in the vicinity of these dc powered transit system. The literature review has shown that based on site conditions, a floating system with ungrounded substations, smaller substation spacing, and high track-to-earth resistance would be key design considerations to mitigate stray current corrosion in newer transit systems.

The need for a stray current collection system will be eradicated if the level of stray current being produced by the transit system is controlled by rail insulation (unless where stray current leakage is high). The goal of insulating the rail is to control the current at the source and minimize leakage. This "control at source" is achieved by reducing the distance between the substations, maintaining a continuous electrical path, use of better coatings, cross bonding, use of insulated track fasteners, rail boot, coating and insulation of rail troughs, and isolating the tracks in the yards and storage. However, research also shows that there will be a certain amount of stray current leakage in spite of these control measures. This leakage usually happens after a few years of track life or even earlier if the tracks are not maintained and tested routinely.

Stray current leakage cannot be completely eradicated but can be kept within acceptable levels. Some of the newer transit agencies have been successful in achieving the desired levels of stray current. However, the majority of transit agencies still struggle to control stray current corrosion in the absence of national standardized guidelines, limited knowledge of the rail transit operators and shortage of resources and funds. This is compounded by the failure of developing and implementing a regular testing and maintenance plan. Though various studies and research papers have identified the need of standard guidelines, principles and testing procedures in the past, none have been compiled to date in the US.

Based on the survey observations and transit agency personnel interviews conducted during this research the following critical needs of the industry have been identified during:

- Implementation of improved rail insulation (track-to-earth) techniques
- Standardization of regular testing program for all transit agencies
- Standard testing methods for stray-current and their limiting measurements based on baseline survey

- Guidelines for acceptable stray current control
- Ongoing track maintenance program (keeping rail track-bed areas clean and well-drained)
- Proper placement of substations along the track using traction power and stray current corrosion modelling

Although many transit agencies have developed their own criteria, it is often unknown how the initial limiting voltage and current values were determined and justified for the criteria. This is especially true when the rail transit industry in the US has not standardized any acceptable limits of negative return resistance.

3 Stray Current Design, Mitigation, and Testing by dc Rail Transit Systems

The absence of specific national SCC/mitigation standard or guideline in the US, necessitates the need to produce contemporary standards and guiding principles for the transit providers and corrosion consultants to match the advancements made in other sectors of the rail transit system.

Real case studies on issues related to stray current effects from transit agencies were used in preparing this chapter and the consolidated guidelines and recommendations for TRB. Some of the case studies include;

- Stray current analysis of national and international transit agencies which includes, European transit agencies, Australian transit agency, and South East Asian transit agency.
- Analysis of stray current corrosion and damage to neighbouring utilities from the operation of multiple national and international agencies.
- Review and by participation in national and international transit agency maintenance and testing programs.

The literature research conducted helped to achieve the understanding of the current industry practices, both national and international, and the criteria for the mitigation of stray currents. In the absence of any national standards and guidelines, international standards [63-68] were studied, especially with respect to their relevance to the local US transit system.

3.1 TRB Research

This part of the work involves the development of a guidebook on design and sustainability of stray current control for Transit Cooperative Research Program (TCRP), with external funding received.

The overall objective of TCRP 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, including:

- A primer that explains all significant issues in readily understandable terms for non-technical personal
- A compilation of case studies (third rail and overhead contact)
- Guidelines addressed to design and maintenance practitioners
- Historical performance data (based on agency interviews) of third rail and overhead contact
- Recommendations for further research.

This guidebook is the most recent effort undertaken by TCRP to provide a user-friendly framework of consolidated guidelines and recommendations that will help in mitigating and/or eliminating stray current leakage from dc operated rail tracks using the data collected from transit agency and corrosion consultant interviews, stray current corrosion survey questionnaires, and field testing. This guide presents a progression from initial considerations of establishing a base line survey for investigating the potential stray current risk to recommending mitigation and collection methods during construction and operation. Figure 17 below provides a graphical representation of the approach taken to complete various tasks for the research carried out under the TRB program.

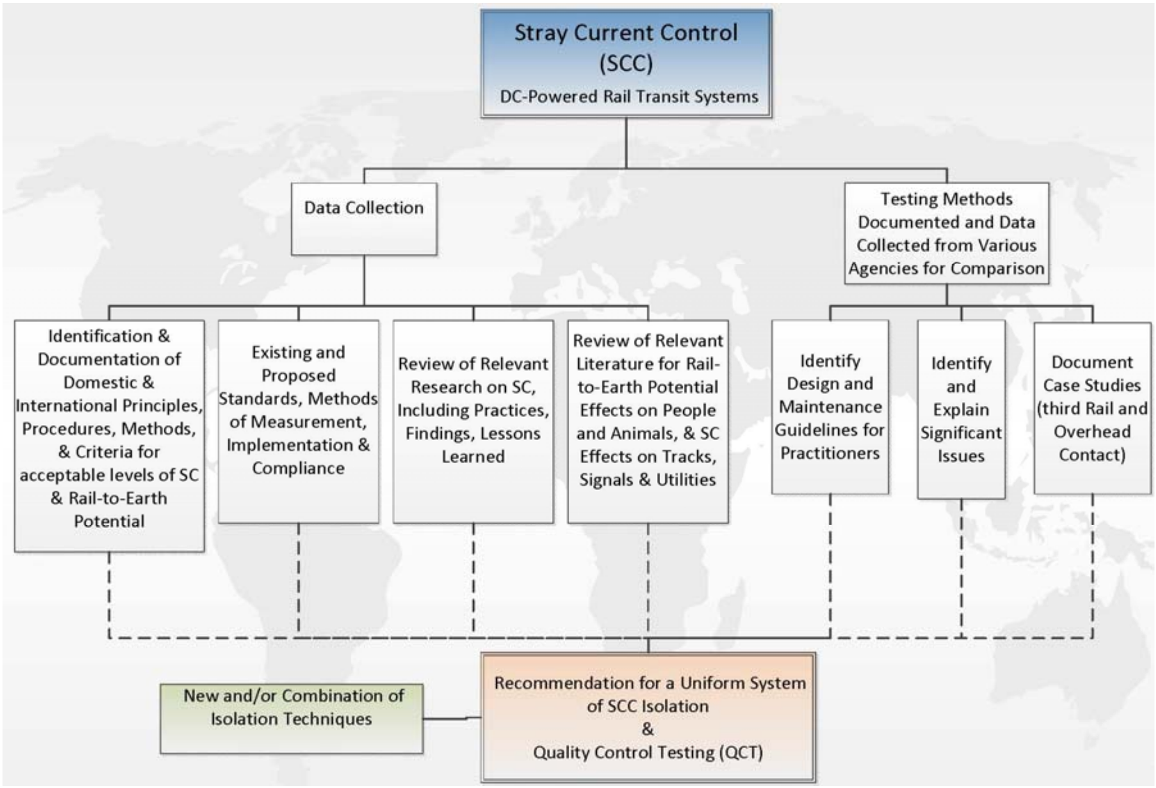


Figure 17: Process Layout for SCC Research Program under TRB

3.2 Transit Agency Questionnaires

An initial desk study of numerous dc powered transit systems was carried out to understand the standard practice(s) 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 TRB (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 any existing and/or previous issues. Table 7 provides the list of national and international agencies that participated by either responding to one of the questionnaires or by agreeing to a telephone interview.

Table 7: Transit Agencies who responded to the Questionnaire

Transit Agency Name	
MD MTA – Baltimore	New Jersey Transit – New Jersey
BART – Oakland	RTA – New Orleans
Charlotte Area Transit System - Charlotte	NYCT – New York City Transit
CTA – Chicago	SEPTA – Pennsylvania
City of Calgary, LRT – Canada	Valley Metro – Phoenix
Copenhagen Metro – Denmark	TriMet – Portland Oregon
RTD – Denver	Public Transport Victoria – Australia
Edmonton Transit System – Canada	Rio Metro Concession – Brazil
GCRTA – Greater Cleveland	Sacramento Regional Transit – Sacramento
METRO – Houston	UTA – Salt Lake City, Utah
LA METRO – Los Angeles	Sound Transit – Seattle
Manchester MetroLink – Manchester UK	Toronto Transit Commission – Canada
MTA – Maryland	Via Quatro Line 4 – Sao Paulo Brazil
MBTA – Massachusetts	WMATA METRO – Washington
Metro Transit – Minneapolis	Yarra Trams – Victoria, Australia

An introductory questionnaire (short questionnaire), as shown in Figure 18, was emailed 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, there are a few who had completed the questionnaire under conditions of complete anonymity, and therefore their names are not listed in Table 7. A matrix listing the responses received from some of these transit agencies is provided in Appendix A[1].

[1] Responses to the questionnaire are based on the survey results between 2012 and 2014. The answers provided by transit agencies have not been vetted with the actual data, design, and/or configuration for their transit system. Names of transit agencies are kept anonymous at the request of transit agency representatives.

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 and Contact person name and Telephone Number.

2. Type of power for the system?
   a. AC ☐ b. DC ☐ c. Other ☐ (specify)__________________

3. Type of rail transit system and total miles for each system?
   a. Heavy ☐________miles b. Light ☐_______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) __________________

9. What is the average spacing between stationing?
   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________________________

Figure 18: Short Transit Agency Questionnaire (TRB)

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

- 50% of the transit agencies and/or their consultants reported being aware of a stray current corrosion issue at their system. 16% responded that they are not aware of any stray current corrosion issues at their system and the remaining 34% did not respond to this query.
- 100% of the transit agencies responded to the question on the substation spacing. 80% indicated that the spacing between most of the TPS is < 1.6km. However, there are a few sections where the distance ranges from > 1.6km to < 3.2km, which is a preferred SCC measure.
- 80% of the transit agencies responded "Yes" to the question on having conducted the base line survey of which roughly 30% acknowledging the fact that the survey was only conducted on some of the newer lines. The base line survey is explained in detail in Chapter 5.
- All with the exception of one US transit agencies responded to the question on limiting values for rail-to-earth resistance maintained on their tracks. Following is the breakdown of their response:
    - 23% maintain 250Ω/300 track metres

- 54% maintain 500Ω/300 track metres
- 15% maintain 1000Ω/300 track metres

The remaining one US transit agency either did not respond to this query or stated that it is lower than 100Ω/300 track metres. Compared to this 50% of the international transit agencies responded that they follow the BS EN 50122-2 and the remaining international agencies either did not respond or presented numbers ranging from 5Ω/300 track metres to 250Ω/300 track metres. The rail-to-earth resistance is a critical parameter as it is one of the first lines of defence against the stray current leakage. This is further defined in detail with the help of a simulation model in section 6.6.5

As expected in these kind of research surveys, some agencies were less responsive than others. In general, the data sample collected as part of the short questionnaire served its purpose of an initial analysis and warranted the development of a more detailed questionnaire (long questionnaire).

Based on the transit agencies willingness 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 emailed to the transit agencies. Though 85% of agencies had initially agreed to contribute to this long questionnaire, yet only 35% of them actually responded. Out of the 35%, some of the agencies completed the questionnaire with a request of anonymity. Figure 19 represents a sample response of the long questionnaire from one of the transit agencies.

1. What are the type, size and cross-section of the rail used? If sketches are available, please send to saud.memon@arup.com.
   Subway running rails: 100ARA-A (old) & 115RE (new lines & replacement rails)
   Streetcar running rails: 115lb head hardened (replacing old 100lb).

8. What is the largest spacing between two power stations?
   Subway: 2.6km
   SRT: 2km
   Streetcar: 9.2km (not a typo!)

11. What guidelines and/or national/international standards were followed for the baseline survey?
    None are listed in the baseline surveys.
    For the track to earth resistance tests, TTC standard is 250 ohm/km.

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 3-4 years

27. How long have the repairs been on-going?
    Repairs are always ongoing due to the track to earth resistance survey, rail replacement, field investigations due to issues, and maintenance of existing mitigation devices (rectifiers, anodes, etc).

29. Is there a log of the maintenance conducted to address the stray current corrosion?
    No log.

35. How many stray current corrosion repairs are typically made per year?
    On average 5-6 per year.

41. What is the estimated annual cost for stray current corrosion repairs excluding the consultant fee?
    $600,000 XXX. This does not include Track Maintenance work.

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?
    The Consultants have used NACE and IEEE, and we have our own design standards.

Figure 19: Sample Questions from Long Transit Agency Questionnaire (TRB)

A matrix listing the summary of the agency response findings, is provided in Appendix B[2]. Following is a synopsis of the key findings/responses gathered from the long questionnaire and face-to-face interviews with the transit agencies and/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

[2] Responses to the questionnaire are based on the survey results between 2012 and 2014. The answers provided by transit agencies have not been vetted with the actual data, design, and/or configuration for their transit system. Names of transit agencies are kept anonymous at the request of transit agency representatives.

of which is elaborated in the literature research chapter and in section 6.6.2 with the help of a simulation model.

- 100% of the transit agencies responded to the question on the TPS spacing. This longer questionnaire included a query about the largest spacing between two TPS's. Most of the transit agencies stated that the largest spacing between two TPS's is < 3.2km, 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 national transit agencies mentioned that they have their own design criteria. They elaborated that this criterion defines 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.
- 33% of the national 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, in the absence of regular testing to ascertain if recommended limiting values are maintained indicates the need of better understanding and implementation of the guidelines proposed in those manuals.
- 95% of the transit agencies acknowledged that they either have stray current issues and/or have encountered one 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 / 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 national 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 the stray current leakage in check.

- With the exception of some transit agencies, none of the agencies shared the information on the cost of mitigating and/or repair of track due to stray current issues.

3.3 Transit Agency Questionnaires

During the coordination process for the questionnaire it became apparent that some of the transit agency employees did not know the specifics of the corrosion mitigation for their system. In some cases, the questions were either relayed to the corrosion consultant working with that transit agency and/or where the agency did not work with a corrosion consultant, the questions were left unanswered. This lead to the need to interview a cross section of corrosion consultants to get their viewpoint based on their experience with transit agencies. Table 8 highlights the list of corrosion consultants that participated in the interview process.

Table 8: Corrosion Consultants Interviewed

Corrosion Consultants	Contact Person Name
Corrpro (International)	S. Singh, D. Lindemuth
UTRS (now with STV)	E. Wetzel
V&A Engineering	G. Willson
LTK	A. Haiko
Parsons (International)	K. McCaffrey
Intertek (International)	D. Buxton & P. Aylott

Interviews with some of the corrosion consultants proved more beneficial where the stray current problem and its remediation was discussed at length. In general, it was unanimously agreed by all the consultants that there is a dire need for a guideline to address the design, testing and maintenance of the stray current process. Some consultants were of the viewpoint that the transit agency staff needs to be trained in carrying out the stray current measurements, whereas others opposed the idea suggesting that all testing should be carried out by experienced consultants.

Though many of the agencies did not want to share the transit agency specific data and requested anonymity, the above-mentioned 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 the study of the responses to both the questionnaires, and interviews of transit agency personnel and corrosion consultant, the following critical needs of the industry have been recognized:

- 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 TPS along the track using traction power and stray current corrosion modelling
- Standardization of regular testing program for transit agencies
- Standard testing methods for stray-current and their limiting measurements (based on baseline survey)

3.4 Survey (Interview) Matrix

The information received from the transit agencies in response to the two surveys was collated in form of a matrix to perform the analysis. This information included specifics like environmental, operational, physical, and stray current data relevant to the transit agency. A sample of the data collected and analysed is presented in Table 9 below for three national and one international agency (results of the analysis are discussed in chapter 5). Most of the transit agencies provided information with a request for anonymity to avoid disclosure of any proprietary information. Thus, the specific transit agency name has not been disclosed.

Table 9: Transit Agency Interview Matrix (Sample)

	Questions	METRO – 1	METRO – 2	METRO – 3	METRO – 4
1	Type of rail system and total kilometres for each system?	LRT – 12km	HRT – 36km, LRT – 142km	Subway / LRT – 1062km	LRT – 69km
2	Special weather condition?	Hot, humid & heavy downpour	Hot, light rain	Use of De-icing salt + Rain	De-icing salt used in winter
3	How old is the system?	2004	1990	1904	1993
4	What mode is used for the power distribution to the system?	Overhead Catenary	Overhead Catenary, third rail	Overhead Catenary, third rail	Overhead Catenary
5	Operational voltage?	750 volts	750 volts	600 volts	750 volts
6	Physical environment of the service?	Urban (shared ROW)	Urban (exclusive ROW)	Semi Urban & Urban	Urban (shared & Excl. ROW)
7	Is there an embedded track section?	Yes	Yes	Yes	Yes
8	What is the type, size, and cross-section of the rail	115RE, Ri59/13, & Ri52	115RE, Ri59/13	115RE, Ri59/13, and Ri52	113lb, 80lb, 59R2, and 35GP
9	What is the average spacing between stationing?	> 1.6 but < 3.2km	> 1.6 but < 2.4km	> 1.6 but < 2km	> 1.6 but < 3.2km
10	Was baseline survey conducted before revenue service?	After the revenue service	Yes (on new lines)	Yes	Yes (on new lines)
11	Is there a maintenance and testing plan in place for the system?	Yes	Yes, visual inspections are conducted	Agency has its own crew for testing	Yes
12	What guidelines/standards were followed for the baseline survey?	Agency design criteria	Consultant provided criteria	Don't know	EN 50122-2, EN 50162,
13	What is the preferred track-to-earth resistance for the system?	250Ω/300 track metres	500Ω/300 track metres & 300Ω/300 track metres	5Ω/300m	5 to 20 Ω-km (Single rail)
14	Does the transit agency currently have stray current issue?	No	Don't Know	No	No (but cable theft is an issue)
15	What are the design measures incorporated in the system to reduce stray current corrosion?	Rail boot & Rebar in track slab	Sacrificial anodes, Insulated pads & direct fixation.	Continuously welded rail, non-grounded system	maintaining high level of rail-to-earth resistance & current collection system
16	What other design provisions are incorporated to control stray current leakage from the system?	Bathtub membrane in special track work sections.	Rail boot	Insulated Pads	Utility drainage, diode grounded negative return

	Questions	METRO – 1	METRO – 2	METRO – 3	METRO – 4
17	Is there a maintenance plan for corrosion repairs and/or track maintenance? What is it?	Regular testing	None	Only when someone complains	Yes, regular visual inspection
18	Is track-to-earth resistance measured as part of the testing/maintenance plan?	Yes	No	No	No
19	Do you have written procedures for your stray current control testing, monitoring and maintenance?	Yes	No	No	Yes (in the process)
20	Have you encountered stray current corrosion-related problems on the system? If yes, how so?	No	Yes, nearby utility line was affected	Yes, rails and clips have been replaced	corrosion of the rail observed during rail replacement
21	Is historical corrosion and repair data available? Can it be reviewed?	Yes - provided	No	No	Not readily available
22	How many stray current corrosion repairs are typically made per year?	None	A major repair in process	Don't know	Embedded rail replaced
23	Has the frequency of stray current corrosion related problems decreased or increased with time?	Decreased	Increased	Data not available to answer	Data not available to answer
24	"Lessons learned" from the stray current corrosion incidents and/or repairs?	Embedded section is a challenge	Regular inspections and testing is necessary to avoid major failures.	Maintenance plan, Guidance and Standards needed for the repairs.	Insulation of embedded rail in shared ROW is a challenge
25	What stray current design specifications or manuals have been the most helpful in the past?	Design Criteria Manual, NACE and IEEE Standards	NACE and IEEE Standards	Transit agency design criteria	EN Standards, and Rail Regulator Tramway Technical Guidance Note No. 3 – Stray Current Design

Worth documenting here is the fact that out of the transit agencies surveyed and questioned, the ones that perform regular testing of the tracks are the ones that have less stray current problems.

3.5 Transit Agency Essentials and Corrosion Issues

The aforementioned data collection exercise (Table 9) 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.

A decision matrix was developed to narrow down a select list of transit agencies for further detailed analysis and presentation. Four (4) representative dc powered rail transit systems from the agencies surveyed 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 1) an agency with relatively newly constructed tracks, 2) an old agency, 3) an agency with tracks under construction (both LRT and Heavy Rail Transit (HRT)), and 4) an international transit agency with third rail and overhead contact systems.

A summary of the case studies on these four (4) agencies is described in the subsequent sections[3]. This information has been gathered from in-person interviews, site visit, and collecting live testing and maintenance track data.

3.5.1 Houston METRO

The Metropolitan Transit Authority of Harris County, Texas (METRO) comprises of approximately 20.6km of LRT. This includes the recently opened (December 21st, 2013) North Red Line Extension of approximately 8.5km and the original Red Line of approximately 12km. The 20.6km Red Line (Figure 20) runs from Fannin South Station along Main Street through Downtown, the Museum District, the Texas Medical Center, University of Houston-Downtown, and ends at the Northline Transit Center/Houston Community College (HCC). The original 12km of Red Line operates along the Astrodome to the University of Houston and started revenue service in January 2004.

[3] 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, and/or may have updated their stray current collection and mitigation techniques. Names of transit agencies are kept anonymous at the request of transit agency personnel.

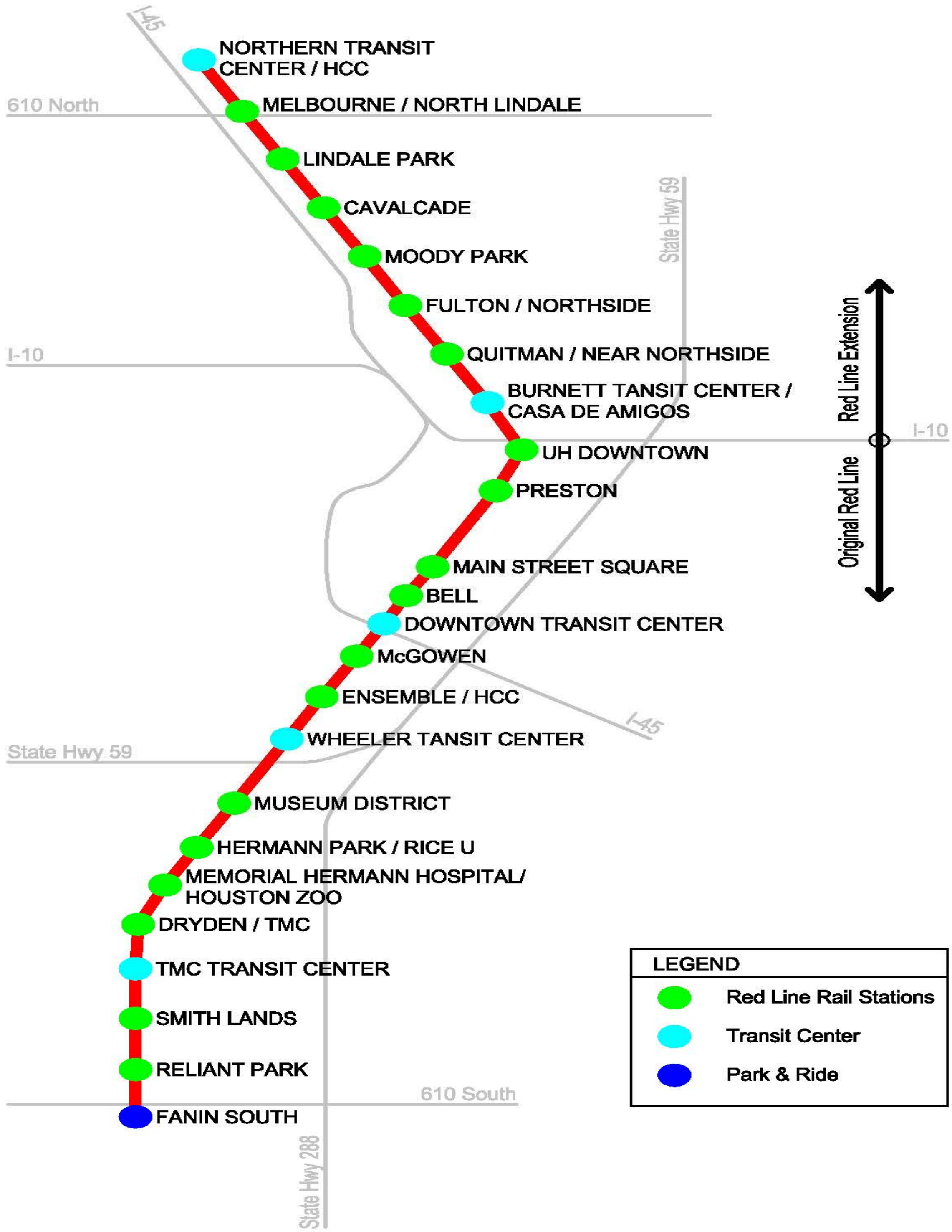


Figure 20: Houston METRO Red Line Map (Provided by METRO)

The METRO system is powered by 750 volts of dc via an overhead catenary system (OCS) with a total of 13 TPS (eight on the original Red line and five on the Red line extension) spaced at not more than 1.6km apart (with an exception of one location where the distance is close to 2km). The negative return system is through the running rails. There is a shop and yard facility which is electrically isolated from the mainline system (as recommended during the literature search). The TPSs are located at the Yard, Reliant Park, Holcombe, Hermann Hospital, Wichita, Alabama, Pierce, Franklin, Burnett, Fulton, Frawley, Melbourne, and Neyland. At the time of the interview the extension line was not in revenue service, so the interview was focused on the issues on the existing Red line.

The track is mostly embedded (95%) with an approximately 1.3km long direct fixation track over an elevated section, and a small section of ballasted track. The transit system uses 115 RE rail 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 re-enters 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, thereby sparing the surrounding utilities and infrastructure from corrosion. Test stations are provided at approximately 107 m intervals for the Red line extension and at approximately 150 m intervals for the original Red line to provide measurements of track-to-earth resistance.

At gaps around bathtub, concrete paver locations, and around special track work, FX-120 polymer is used to fill in the gaps. Injection of silicon material along the rubber boot interfaces increases the track-to-earth resistance in those areas. All items that are connected to the running rails (e.g. switch heaters, signalling system, and rail lubricators) and to the negative buses within the substation are suitably insulated making sure that there is no link between the grounding structures and the negative return.

An important element of the stray current control for METRO is the liaison with the utility owners that have utilities closer to the Red line. Numerous utilities exist along the right-of-way including some major lines like Center Point Energy's gas line and municipal water pipelines. In addition to the stray current design provided by METRO, the local utility owners in the vicinity of the METRO line conduct testing on their pipelines and maintain their own sophisticated CP systems to protect their infrastructure.

Figure 21: Section of Flangeway Filler Rail Boot during Construction

Figure 22: Steel Reinforcement for the Embedded Slab Track

The preferred rail-to-earth resistance of the embedded track is 100Ω/300 track metres and the conservative contract requirement is of 250Ω/300 track metres. These resistances were established by the corrosion consultant after conducting the rail-to-earth testing of the tracks using ASTM standards [85]. Figure 21 above shows the rail boot installation on the rail on an under-construction section of the tracks. Figure 22 shows the section of the rail which sits on reinforced concrete slab that also has the steel mat for corrosion control. In the early years of the transit service, METRO did not have any track maintenance, inspection plan or guidance on stray current corrosion included in their design criteria manual. However, in 2007 the METRO developed a design criteria manual that was for both LRT and Bus Rapid Transit (BRT) systems which includes a chapter on stray current corrosion. This was followed by stray current system testing such as; track-to-earth resistance, track slab stray current flow, and audio frequency tracing measurements being conducted as feasible.

<u>Testing Methods:</u>

As part of the overall track corrosion maintenance and testing survey the following tests are conducted:

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

The testing is conducted every three to five years based on the track performance.

Figure 23: Utility Testing Station Houston METRO

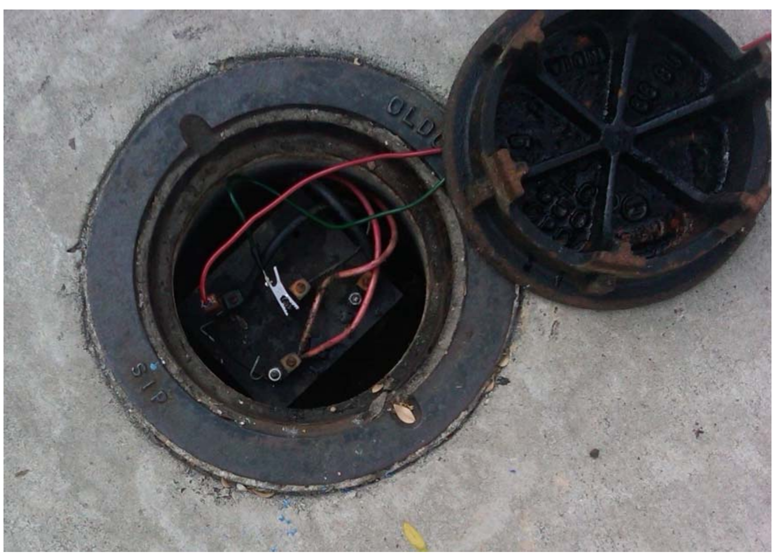


Figure 24: Utility Testing Station Houston METRO

<u>Findings from Testing and Corresponding Corrosion Issues:</u>

Results of the testing conducted soon after the revenue service revealed that most of the track sections are essentially in compliance with the 100Ω/300 track metres 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 right-of-way (ROW) were also tested where minor to negligible stray current effects were noticed. Most of these areas were selected for regular periodic testing. METRO now conducts testing of the track once every three years for the entire section and once a year for the section of the track that runs parallel to the Texas Medical Center (TMC). Though the track rebar system has been very efficient in keeping the stray current contained as designed, METRO conducts periodic testing of some of the critical locations including the areas close to TMC and utilities within the ROW.

To understand the testing procedure, testing need, and the method's effectiveness, actual ground testing was observed and performed (for some tests) as a part of this thesis work. Details of the testing and respective results are discussed in Chapter 4.

Conclusions:

When asked what the key issues are; METRO staff indicated that they would rather not construct an embedded track within the urban area. In situation where there is no other alternative, they would like to ensure that the rail is completely isolated (use of modified rail boot) in combination with a possible SC collection system. This would ensure minimal to no leakage of current to the earth or the neighbouring utilities. Moreover, as recognized in the literature review, METRO would like to see more researched guidelines and principles supporting the limiting values for stray current mitigation [85, 86].

3.5.2 New York (NY) City Transit – MTA

Since the earlier days of its service in 1904, the New York Metropolitan Transit Authority (MTA) has grown to be one of the top six busiest subway systems in the world. Its total number of track is 1350km with approximately 60% of the track kilometres underground and 468 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 1930, the system has seen a lot of upgrades including the one observed during the data collection for this thesis in November 2011 and then in March 2012 when there was work being done on construction of additional tracks on the existing and new transit routes.

The NY MTA system is powered by 650 volts of dc via the third rail with substations receiving as much as 27,000 volts from the power plants. The signals, station and tunnel lighting, ventilation and other miscellaneous line equipment is powered by ac. The substations spacing varies from 0.8km in the newer lines to not more than 2.4km in some of the older lines (this is after construction of some interim substations 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 slowly being replaced. 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 10Ω/300 track metres at its worst. Diode drains along with track bonding is used to provide stray current control with cross bonding every 150 to 300 metres.

Figure 25: NY Subway Map (http://web.mta.info/maps/submap.html) (March – 2014)

Figure 26: Section of On-going Construction with Concrete and Wooden Ties.

The MTA does not have specific criteria and/or principles for the operation and maintenance of stray current corrosion and has a corrosion control task force that handles the corrosion related complaints. Thus, as stated in the literature review section of this thesis, the approach to address stray current issues is more reactive than proactive. There is a corrosion control guide that was structured in 1984 by Sammon [56] that some staff members still have copies of, but it is rarely ever used as a reference for the stray current corrosion issues.

Testing Methods:

There are no periodic inspections or testing conducted on the transit system. The corrosion staff at MTA is responsible for the corrosion surveys and testing is conducted mostly to address a prevailing complaint rather than as a routine proactive approach. The corrosion testing crew is on duty 24 hours a day with the goal to keep the corrosion issues at the minimum.

Figure 27: Water Pipe Utility Test on Bridge – New York MTA

<u>Findings from Testing and Corresponding Corrosion Issues:</u>

Being this old of a system (in service since 1905), issues are expected to happen and have been taken care of in the past. However, the recent upgrades to the NY MTA have rendered the previous corrosion records immaterial. MTA does not keep a database of the existing corrosion issues and there is no report generated to present the issue, mitigation, and the conclusion. Following are some of the issues that MTA staff mentioned that they have to face on recurring basis:

- water main failures/corrosions,
- corrosion of rail spikes,
- loss of expansion joint bonds of the elevated structures leading to corrosion of steel components, and
- failure of old lead cables.

<u>Conclusion:</u>

When asked what the key issues are; MTA staff indicated that they would like to upgrade all the tracks that are old or have not been upgraded yet and change the fastener clips. During the interview they also implied that not having a source document (guideline/

recommendations) for reference and standards makes their job difficult and they would like to see a uniform guideline and/or standard to be followed across the industry [87].

3.5.3 Los Angeles (LA) County – MTA (LA – METRO)

Since opening in 1990, LA Metropolitan Transportation Authority has grown to become an integral part of the county's transit system where several additional works are still being considered and/or being carried out currently. METRO has a combination of light and heavy rail and is currently operating approximately 148km of LRT and HRT with 91 station locations. The heavy rail lines (Red and purple) 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 ROW in the future. The routes run in a mix of environment, including; at-grade, elevated, and underground. There are six METRO lines currently in operation as detailed in Table 10.

Table 10: Los Angeles Metro Lines

Line Name	Opening	Length (km)	Stations	Type
Blue Line	1990	35	22	LRT
Red Line	1993	26	14	HRT
Green Line	1995	32	14	LRT
Gold Line	2003	31.9	21	LRT
Purple Line	2006	10.3	8	HRT
Expo Line	2012	13.8	12	LRT
Crenshaw	Under Design Build Contract			LRT

The HRT system is powered by 750 volts of dc via the third rail whereas the LRT system is powered by 750volts dc via the OCS with running rails providing the negative return for both the systems. The substation spacing varies from 0.8km to 3.2km for both the LRT and HRT system. The track is mostly ballasted 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 500Ω/300 track metres of rail whereas the embedded section at-grade crossings/city streets is 300Ω/300 track metres of rail. Wooden ties and spikes are used for the tracks in shops and yards and are reasonably well isolated from the main line.

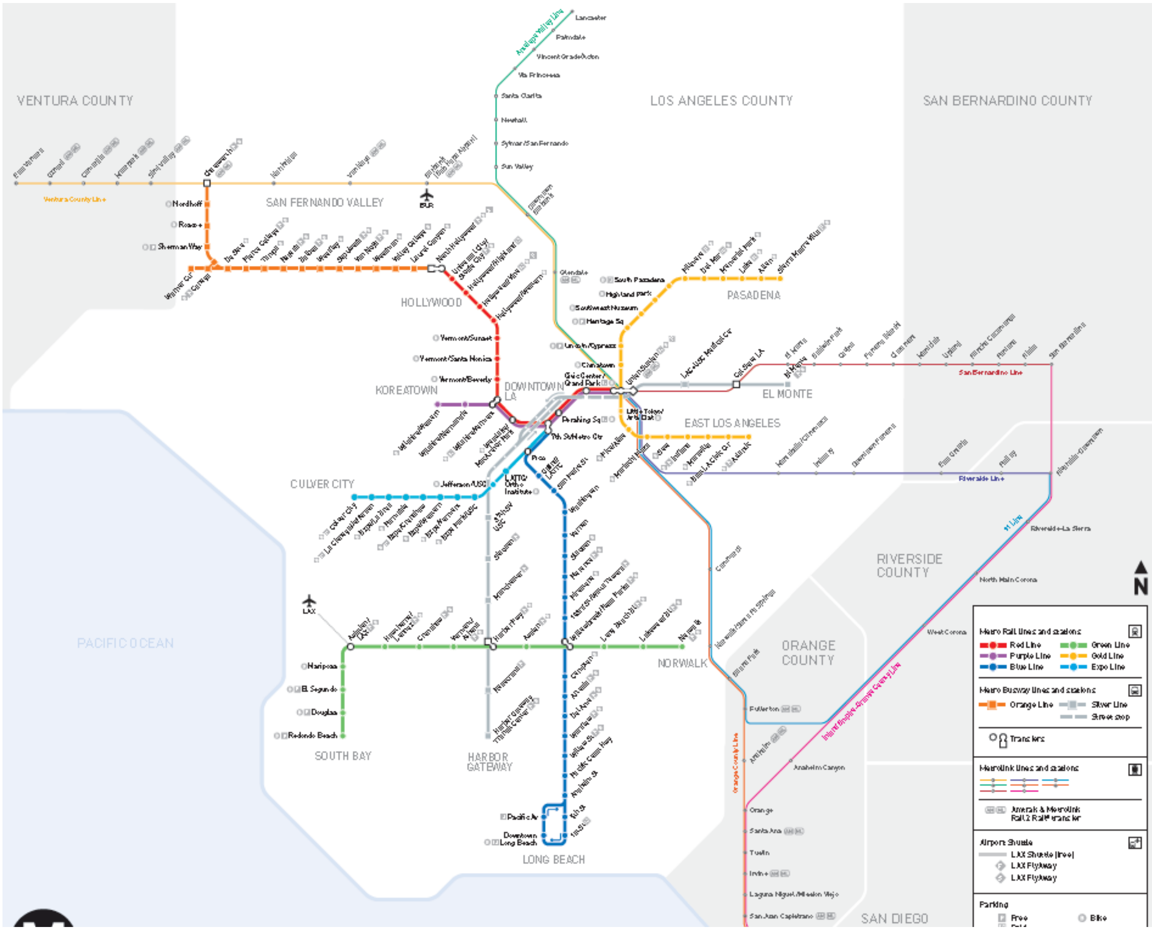


Figure 28: LA METRO Map (http://www.metro.net/riding/maps/) (March – 2014)

LA-METRO does not have a track maintenance inspection plan, nor does its design criteria manual include any guidance on stray current corrosion. The corrosion issues are dealt as they arise. METRO is currently working with a consultant to conduct survey and testing of sections of the line and to generate some suggestions to mitigate the stray current corrosion.

Testing Methods:

Until recently there were no inspections or surveys conducted on the transit system and typically utility companies and/or the local residents would report potential stray current issues to METRO, whom in turn would take any mitigation action as needed. However, due to the raising corrosion issues and the expansion of the LRT system, METRO now uses the services of a corrosion consultant. The consultant conducts pipe to soil corrosion testing and provides mitigation recommendations. This consultant is also working on preparing an updated Operation and Maintenance Manual to include maintenance procedures to help mitigate stray current and is providing stray current training to METRO staff.

Findings from Testing and Corresponding Corrosion Issues:

Results of the recent testing conducted by the transit agency reveal that the stray current corrosion activity has generally increased with the following recurring issues:

- Corrosion of fire protection pipe system due to failure of CP system
- Number of other CP locations not functioning as designed.
- Corrosion of rail spikes
- Areas of low track-to-earth resistance along the lines
- Possibility of a substation being grounded which results in stray current leakage

Figure 29: Corrosion of Pipes at Station Facility (LA METRO)

Conclusion:

Periodic testing and monitoring of the testing locations were identified as the key issues at METRO and the staff indicated that they would like a consultant to keep a restricted online database of the system including the results and GPS locations of the testing areas. This will provide the transit agency, the consultant, and the utility owner a log of the updated test results. Additionally, METRO would like to see some more researched guidelines and principles supporting the limiting values for stray current mitigation [88].

3.5.4 International Transit Agency

The International Transit Agency comprises of approximately 32km of LRT/tram line powered by 750V dc via an OCS and a suburban rail line (Rapid Transit). The LRT includes the recently opened extension line (approximately 7.5km) along one of the routes. The LRT runs through the urban shared and dedicated ROW with embedded, bi-block slab, and ballasted track sections with a total of 52 stops (Stations). The TPS are spaced at not more than 1.6km apart with an exception of one span where the distance between the TPS's is slightly longer than 1.6km. The negative return system is through the running rails, cross bonding, and the collector cable that is bonded to the stray current mat (wire mesh). The existing depot is broadly divided into two areas; a stabling 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 earthed to the building earth to prevent touch potentials. The maintenance area is only 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.

The Transit Agency uses flat bottom 113 lb rail with concrete ties with insulated rail clips for the ballasted section, 80 lb 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, it uses continuously welded rails, direct fixation fasteners, cross bonding, tie and ballast at-grade track, and 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 m. Test stations are provided at approximately 91 to 150 metres interval to provide measurements of track-to-earth resistance.

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

Figure 29a: Embedded and Ballasted Section

<u>Testing Methods:</u>

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
- Cell-to-cell potential gradient measurements

This testing occurs every five 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 is not 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 additional measures, or changes to the basic requirements are recommended. 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 a part of this research work.

Conclusion

When asked what the key issues are; Transit Agency staff indicated their satisfaction with the adequacy and efficiency of the stray current corrosion levels and mitigation measures 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 more 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 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.

3.6 Summary

Based on the literature research and the transit agency interviews stated above, it is evident that design criteria documents do not exist or are developed as an aftermath of corrosion problems. This fact combined with the absence of testing or survey information renders the reasoning behind the limiting criteria suggested in such transit agency manuals unclear. It may be inferred that criteria suggested in such manuals were developed based on the information from other transit services. To-date some of the older transit agencies do not have criteria in place for handling stray current corrosion problems or for that matter any operation or maintenance plan or a financial budget. They handle corrosion issues as they occur and prioritize them based on severity and the available budget.

An opinion shared by many industry experts is that, in the absence of written guidelines and/or standards for stray current control, mitigation, testing and maintenance, it is difficult to standardize a uniform approach for dc transit system providers. There are a few technical papers and reports (referenced in literature review above) that define the critical values for some of the tests performed by the transit agencies. This includes the ASTM standard for track-to-earth resistance [62]. However, in most instances, the use of the limiting values for the stray current control, 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.

Assessment of potential corrosion resulting from stray current should be part of the planning and design process at the very inception of any project and the testing of the stray current corrosion must continue through the revenue service. However, based on interviews conducted during the course of this thesis it was apparent that most of the transit agencies discussed above had not conducted a pre-revenue testing and do not have a regular testing and maintenance plan.

It was also observed that the transit agencies are not keeping logs or records of corrosion issues caused by stray current and the money spent to mitigate those corrosion problems. This kind of tracking would be beneficial to the rail industry in assessing the economic and logistic burden borne by the rail transit agencies as a direct impact of stray current corrosion. Though most of the transit agencies interviewed had at least one corrosion staff and/or traction power engineer on payroll, due to limited knowledge and understanding of the issue coupled with the absence of guidelines, they relied on outside consultants to conduct their stray current corrosion testing. This fact was further verified when the transit agency staff forwarded the survey questionnaire to their respective consultants for completion. The staff, in general, was however found to be cognizant of the seriousness of stray current corrosion issues. They were aware of the need and benefit of corrosion tests required and realized the importance of maintenance of the track. They also cited lack of available funds as a restricting factor. The alternate to this lack of funding issue is that the transit agency staff should be trained on the fundamentals of stray current and subsequent testing, control, and mitigation to control stray current levels.

Additionally, 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.

4 Field Testing Procedures and Maintenance

Rails are isolated to control stray current at the source and stop leakage. As detailed in the literature research section, this “control at source” is achieved by reducing the distance between substations, maintaining a continuous electrical path, the use of better coatings, cross bonding, the use of insulated track fasteners, rail boot, coating and insulating rail troughs, and isolating tracks in the yards and storage.

The efficacy of insulation systems used around the rail to keep the leakage current below acceptable levels is of limited duration [89]. Even if accomplished, high rail-to-earth resistance is observed only for a few years post construction and is more challenging to achieve if tracks are not maintained properly.

Regular inspection, testing, and maintenance of the transit system is imperative to ascertain that stray current does not leak into the utilities and surrounding metal objects. Typically, it is challenging for transit agencies to keep up with the testing and maintenance of tracks. Consequently, all the dirt, debris, rail shavings, cable shavings, salt, and water from the tracks contribute toward stray current leakage. In areas of high stray current leakage different isolation and/or current collection techniques are used in addition to the rail boot. These methods, when implemented in conjunction with the rail boot, have significantly reduced stray current related problems, including: signal failures, controlling rail-to-earth voltages, minimizing recurring cost of repairs, and the damage to the public infrastructure [89]. All mitigation methods installed to control stray current corrosion require periodic inspection during operation along with the inspection of the rail potential which needs continuous monitoring of the system to avoid risk of any major situation [89].

Currently there are no fixed industry standards that would guide a transit agency on the type of testing and the recommended frequency of these periodic inspections. Most transit agencies have their own inspection schedule. There are still some transit agencies that do not carry out any inspections/testing and react only when there is a complaint by a utility owner [90]. During the literature search a draft APTA standard “APTA RT-S-FS-005-03” [69] was identified and studied. Though not complete, this draft standard provides rudimentary minimum requirements for the inspection, maintenance and testing of rail transit stray current control systems. This draft standard, produced in July 2004, underlines the inspection criteria and maintenance standards for passenger safety, and highlights the importance of special safety equipment being operational and reliable. Due to its incomplete status, the transit agencies interviewed had not heard of this standard.

Additionally, the European standards, EN 50162:2004 [63] and EN 50122-2:2010 [65] do briefly mention tests, measurements and principles behind continuous and repetitive monitoring.

In order to better understand various testing methods, two different transit agencies' stray current control surveys were witnessed and scrutinized during the course of this thesis. The details of the testing procedures along with the findings of the surveys performed by the corrosion consultant are discussed below.

- Stray current testing for Houston METRO, Texas (2011/12)
- Baseline survey for Salt Lake City, Utah (2012)

4.1 Stray Current Testing – Houston METRO

The METRO Light Rail System (METRO) is operated by the Metropolitan Transit Authority of Harris County, Texas. This section makes reference to the original 12km track of the Red Line, because base-line testing was conducted before the start of revenue service on the Red Line extension. The track alignment, as depicted in Figure 30, is approximately 12km long with train service from approximately 4 am to midnight. The details of the track alignment and other design particulars including stray current mitigation measures are stated in Section 3.5.1.

Houston METRO is amongst one of the few transit agencies that has a regular testing program. The agency has worked with a corrosion consultant that performs the overall survey of the alignment every three years. Depending on results of the corrosion survey, follow-ups are usually performed within three to six months of the initial survey to verify the results and to perform repairs to the mitigation equipment.

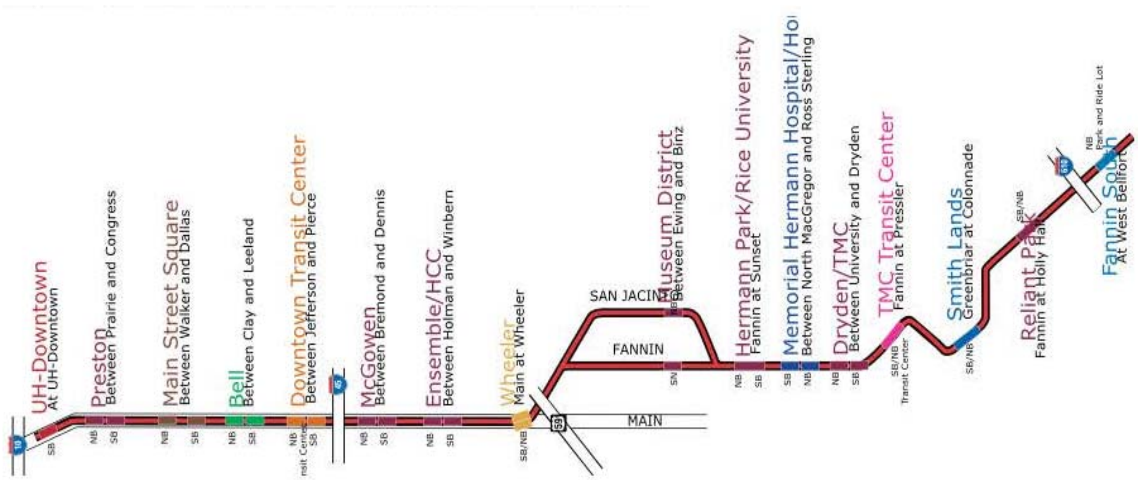


Figure 30: METRO Houston LRT Corridor (provided by METRO)

4.1.1 Equipment

The testing required a high-input-impedance voltmeter with data recording and storage capabilities. A Fluke Model 2635A Hydra Data Bucket, as shown in Figure 31, was used for the testing. The 2635A Hydra Series II Data Bucket is a 21-channel data logging instrument that measures and records the following electrical and physical parameters: dc volts, ac volts, resistance, frequency, and temperature. Depending on the tests to be performed, the connecting wires are plugged into corresponding plug-ins on a handcrafted platform. The platform also includes a 12V battery whereas the Fluke model has the inbuilt capacity of logging/storing data.

Multiple diverse data loggers are available in the market to record the leakage of current and the choice of instrument is budget dependent. The Hydra series used above is a relatively older instrument. New, improved and efficient systems are also available in the market. Standard 12V batteries are typically preferred for ease of carrying, and safe voltage.

Figure 31: Fluke Model 2635A Hydra Data Bucket

4.1.2 Test Methods

The stray current corrosion testing by corrosion consultant took place between July 19 and September 9, 2011. For the purposes of this thesis, the results from the July 19th and July 20th testing are focused upon to understand the efficacy and performance specific tests. This testing was part of METRO's contract with the corrosion consultant (names of corrosion consultant are mentioned in section to perform testing every three years.

Testing methods vary depending on the type of structure under investigation and the source of the stray current. However, potential and current tests are the most frequently performed tests for both static and dynamic stray currents. In this case, testing was divided into the following categories:

- Visual Inspections
- Structure and/or Utility Pipe-to-Soil Potential Measurement
- Track Slab Current Measurement

  Measurement of potentials and current flow on the Brays Bayou Bridge and Main Street Bridge including three Texas Department of Transportation (TxDOT) structures

- Cell-to-Cell Potential Gradient Measurements

Light precipitation occurred during some of the tests that may have lowered the soil resistivity and track-to-earth resistance, giving a probability of a more conservative estimate of stray current activity.

4.1.2.1 Visual Inspections

Visual inspections are conducted to identify any uncharacteristic structure item or impact from other miscellaneous factors at each special track elements like bathtub and rail lubricators. These inspections help identify concrete curb joining the bathtub membranes, and rail boot and/or polymer separations along rail lubricators. If required, visual inspections are conducted in conjunction with physical measurements taken at special track locations identified.

Results:

The consultant conducted visual inspections with the transit agency staff before the actual physical testing of the transit system and noted no adverse findings.

4.1.2.2 Structure and/or Utility Pipe-to-Soil Potential Measurement

This method is commonly referred to as the Utility to Earth potential and is used to ascertain the extent of stray current in neighbouring utilities and infrastructure. These tests are conducted to specify whether the pipe is influenced by the stray current and whether the current is leaving or entering the pipe. Negative potential implies current being picked up by the pipe whereas positive potential is indicative of current discharge [83]. The pipe-to-soil potential can indicate if there is stray current activity on a pipeline.

Experiments have shown that pipe-to-soil potentials will deviate to positive and will fluctuate significantly when a train crosses the location being tested and show minimal variation when the train leaves [91]. This suggests that stray currents, due to dc powered LRT systems, will cause fluctuating voltage gradients in the soil. This fluctuation can be used to determine the severity of the stray current influence. The actual rate of corrosion caused by the magnitude of the pipe-to-soil potential cannot be directly assumed and may be different from pipe to pipe. Moreover, the rate of corrosion is dependent upon a variety of factors, including coating type and condition.

Pipe-to-soil potentials on the City of Houston (COH) water pipelines were recorded at test stations that were installed by METRO during the construction of the system. These test stations have an embedded probe between the pipeline and the tracks at the point of crossing. This point is assumed to be the most probable location for stray current activity along the pipeline. The COH water corrosion monitoring team also performs tests on their testing locations which are different from METRO's.

Pipe-to-soil potential measurements were recorded during revenue service over a 20-minute time period and until at least two trains had passed the location. The potentials were recorded approximately once every second. Unless noted otherwise, the potentials were taken with respect to the embedded probes. Figure 32 below shows a typical test location.

Figure 32: Pipe to Soil Testing Location

Classifications for stray current influence have been previously established for this alignment and are shown in the Table 11.

Table 11: Testing Recommendations – Pipe to Soil

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

The typical level of allowable earth potential gradient is calculated as close to 75 millivolts (mV). However, the values above, along with the recommended criteria, are based on the revenue stray current study for METRO done in 2005 and were provided by METRO Houston [85].

<u>Results:</u>

The potential variation recorded by the consultant for the 58 utility tests ranged from 2 mV to 376 mV. Comparisons between the current utility tests and tests performed the previous year were conducted by the consultant to analyse the variation in the stray current

Ten of the 58 utility tests were performed at six locations within the TMC corridor. Two tests showed potential variation between 75 and 150 mV, and one test showed potential variation greater than 150 mV. Outside the TMC, 48 utility tests were performed. Three tests showed potential variation between 75 and 150 mV, and one test showed potential variation greater than 150 mV.

<u>Conclusion:</u>

The test locations that showed higher potential values were scheduled for retesting by the consultant. If results indicate persistently increased values then mitigation measure would be suggested for those locations based on the severity of corrosion. Retesting showed normal values for all locations with medium and high ranges. The precipitation during the day of testing was attributed for the earlier higher values. None of the utility companies, with infrastructure within the ROW, have complained about higher levels of stray current except the TMC which has failed to provide any proof of higher stray current.

4.1.2.3 Track Slab Stray Current Measurement

These measurements are tracked by METRO's consultant so that the data can be used to ensure an intact negative return system. This would alleviate the impact of stray current on neighbouring utilities and infrastructure by ascertaining an electrically closed path. Current flow in the track slab provides an insight to the magnitude and direction of the possible current leaking from the rails into the earth. This is considered by METRO as the most effective test to evaluate current leakage. The top layer of reinforcing steel is welded to make it electrically continuous. This electrically continuous reinforcing steel mat acts as a collector of stray currents. It is intended to reduce the amount of stray current that can be picked up by adjacent utility pipelines. Test stations providing electrical access to the reinforcing steel are located approximately every 150 m along the alignment.

The voltage drop across two adjacent test stations was recorded along the track slab steel reinforcement during revenue operation. The measurements were made by attaching the recording voltmeter across test stations and recording the potentials at approximately 5-second intervals for a period of 30 minutes and until two trains had passed. The positive lead of the voltmeter was placed at the larger station number (north) and the negative lead was placed on the smaller station number (south). It is known that current flow on the track slab steel will discharge from adjacent sections of rail or track slabs skewing the level of stray current observed. A correction factor for the allowable level of stray current should be applied to the design level to provide a realistic peak of allowable stray current for evaluation on the track slab reinforcing steel mat. Based on the short duration stray current scans measured for this project, the peak-to-average correction factor is approximately 40% [85]. Figure 33 below depicts the test setup.

Figure 33: Track Slab Current Flow Test

The criterion was established in 2005 during the revenue stray current study for METRO and was provided by METRO Houston to correlate the track slab current flow to the severity of stray current activity. The criteria correlate the average measured current flow to three classifications, low, moderate, and high. The criteria are summarized in the Table 12 below.

Table 12: Testing Recommendations – Track Slab Stray Current Flow

Testing Recommendations – Track Slab Stray Current Flow	
Average Stray Current (Amps)	Stray Current Classification
< 5	Low (L)
5 – 20	Moderate (M)
> 20	High (H)

The average stray current flow is used to determine the current flow in the span.

<u>Results:</u>

Test stations for 125 track slab current test spans were located and tested. The current flows in the track slab ranged from -19.9 to 31.9 amperes and the results were compared with previous year's results to analyse the change in stray current leakage.

There were 32 track slab current spans tested within the TMC, all of which showed a low amount (less than 5 amperes) of stray current. Outside the TMC, 93 slab current spans were tested. Of these, 89 spans showed a low (less than 5 amperes) amount of stray current. A moderate amount (between 5 amperes and 20 amperes) of stray current was measured at three of the track slab test spans. A high amount (greater than 20 amperes) was measured at one track slab test span.

Conclusion:

It was the transit agency's understanding that the stray current levels found in this study generally do not result in significant corrosion and no follow up testing was deemed necessary.

4.1.2.4 Bridge Stray Current including TxDOT Structures

These tests are similar to pipe to soil test and are conducted to ascertain whether the structure is influenced by the stray current and whether the current is leaving or entering the structure.

The consultant measured stray current activity in the steel reinforcement of the Main Street Bridge and three TxDOT structures: the I-610, I-45, and U.S. 59 overpasses. Bridge-to-soil potentials were recorded at test stations using an embedded probe located near the bridge reinforcing steel. Bridge-to-soil potential measurements were recorded during revenue service over a 24-hour time period. Figure 34 shows a typical test location.

Figure 34: Bridge Stray Current Test Location

The stray current influence on bridge reinforcement was gauged by the same criteria used for pipelines, as shown in Table 11 above. These values are based on the revenue stray current study for METRO done in 2005 and were provided by METRO Houston.

Results:

The potential shifts at the test location on Main Street Bridge were below 75 mV and categorized as low. The potential shifts at the 10 test locations on the I-610, I-45, and U.S. 59 overpasses were also below 75 mV, categorized as low and warranted no further investigation.

Conclusion:

Due the fact that the test leads were not continuous the data on the Brays Bayou Bridge was not considered. Test leads should be replaced at the Brays Bayou Bridge and additional testing should be conducted to establish the levels and severity of stray current.

4.1.2.5 Cell-to-Cell Potential Gradient

This test is conducted to measure the stray current influences relative to voltage gradients in the soil. Current flow through the earth creates a voltage gradient that is proportional to its magnitude. This test does not necessarily measure stray currents on pipelines or other structures. As part of the testing the potential gradient in the earth was measured at seven locations. The measurement was taken by placing one reference electrode 0.6 meters away from the outside rail on the north bound track and another reference electrode 31 meters away and perpendicular to the rail. The positive lead of the voltmeter was placed closest to the rail, and the negative lead of the voltmeter was placed on the reference cell farthest from the rail. The voltage gradient in soil was categorized according to the same criteria as used for pipelines, as shown in Table 11 above.

Results:

All but two locations had an average potential gradient of less than 75 mV. The test at both locations may not be indicative of a valid ground potential gradient because a residual potential gradient may be present even with no trains active. It was recommended that another test be performed when no trains are active on the system to establish a baseline gradient. After establishing a baseline gradient, that gradient would be subtracted from the gradient measured while trains are active.

Conclusion:

METRO did not provide notable feedback on this except a concluding statement that all locations tested were less than 75 mV per 30 m. potential variation criteria and no further testing was deemed necessary.

4.1.3 Conclusion

A baseline survey for the system was conducted after the rail transit system was in revenue service and most of the testing maintenance is gaged relative to this data. During the development of the baseline characteristics for the system, a main concern was the inherent performance parameters of the embedded track since high track-to-earth resistance performance is challenging to obtain in the embedded track due to the continuous close proximity of the rails and earth, relying primarily on a thin isolation membrane throughout. This allows for increased possibility for current leakage as compared to the ballasted track, thus triggering the need for a continuous track slab reinforcing steel mat. Track slab current flow is an indicator of the locations of low resistance track and has a direct correlation to the level of stray current leakage.

Track-to-earth resistance testing was conducted after the revenue service had started. ASTM standard practices were used and limiting values were recommended. However, the corrosion consultant did not perform the track-to-earth resistance testing during the maintenance testing. In this scenario it would be recommended to conduct the track-to-earth resistance of the tracks to validate the isolation performance in contrast to the limiting track-to-earth values. This test helps in identifying the low resistance value locations along the track length that result in the stray current leakage.

Based on the results and conclusions, the transit agency needs to adopt a more robust annual maintenance plan where the stray current leakage assessment is carried out to cover all the test stations.

4.2 Baseline Survey for Salt Lake City, Utah

The light rail system in Salt Lake City, Utah is referred to as the TRAX (Transit Express) and comprises of four different lines; Blue, Red, Green and Front Runner. Figure 35 below shows the limits of the service and the areas served.

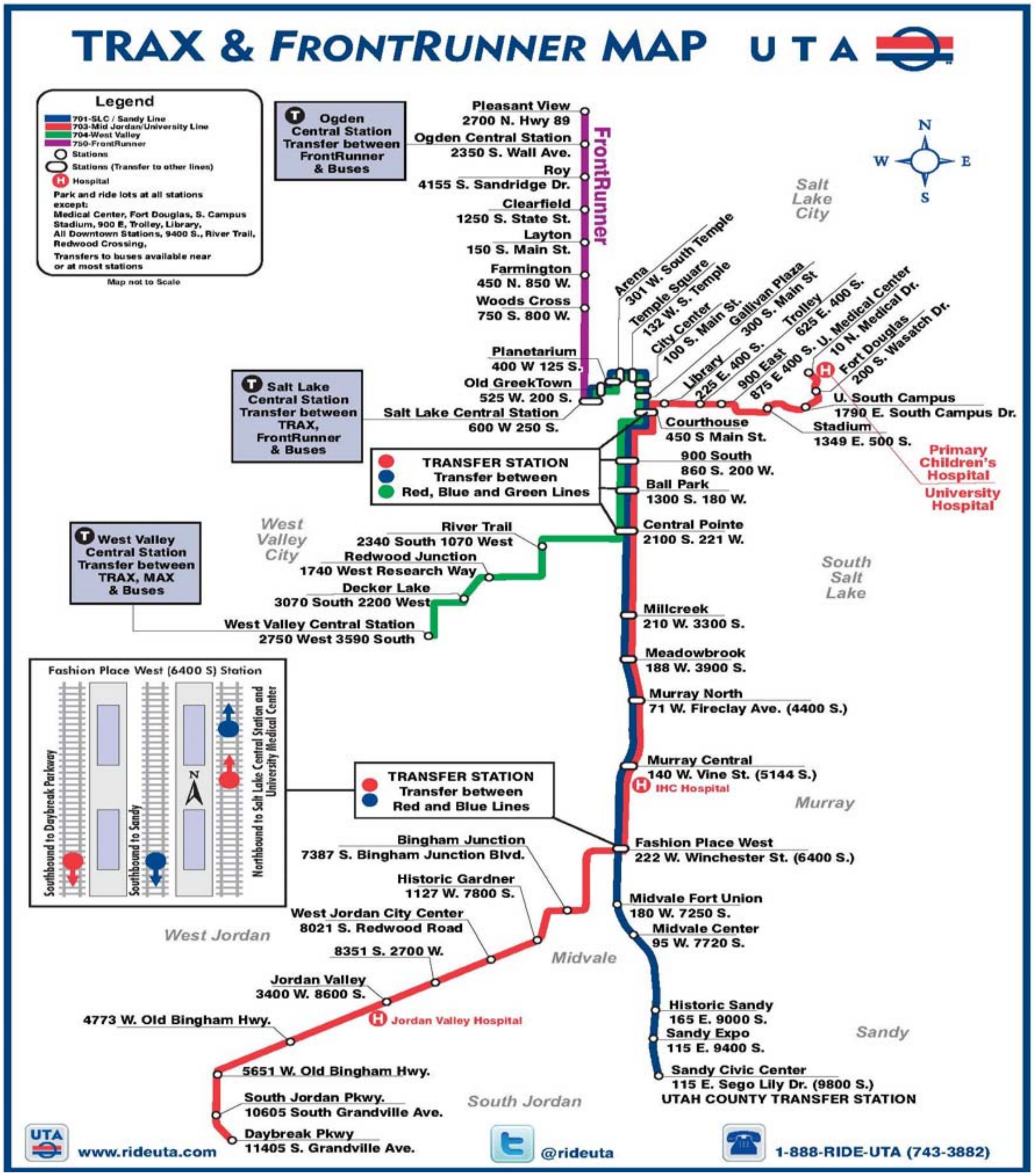


Figure 35: UTA Map (http://www.rideuta.com/ridinguta/routes/routefinder.aspx) (September 2014)

The early stage of Design Criteria development for the Utah Transit Authority (UTA) LRT system, corrosion control modelling indicated that 100Ω/300 track metres would be an optimal value to mitigate stray currents [90]. The UTA LRT system requirements, as embodied in the systems specifications, included a conservative limit of 250Ω/300 track metres (2 rails) for at-grade and a limit of 500Ω/300 metres of aerial to provide an additional margin of isolation. Permissible resistances were attained by the use of insulated tie plates, rail clips, rail boots, and direct fixation fasteners.

A partial "baseline" survey of the system was performed in accordance with the preferred, but less practiced, industry practice of performing track-to-earth resistance testing prior to the first revenue service operation. A corrosion consultant was hired by the contractor to perform the testing on a section of the track that included both ballasted and embedded sections. Track-to-earth resistances were monitored before, during and after construction to detect the variations in the resistance. Track-to-earth field testing was observed in person as part of this research to develop a better understanding of the testing procedure, and to help understand the process of achieving the desired track-to-earth standards before the start of the revenue service.

4.2.1 Equipment

The testing included two multimeters (Fluke 289 and Fluke 116), two 12-volt dc batteries, an automatic timer and cables to run between the testing stations. The Fluke models were used to measure the current, dc volts, ac volts, and resistance. Figure 36 shows the typical equipment used for the testing. The testing equipment depends on the tests to be carried out and the level of accuracy required. As illustrated in the previous section, there are numerous different models of the equipment available and the choice typically depends ease of availability or budget constraints.

Figure 36: Fluke Model 289 and 116 – Embedded Track Section

4.2.2 Testing Methods

Stray current corrosion and equipment testing took place from March 12th through March 14th, 2012. This testing included the section of track from the airport to the downtown area and was part of the corrosion consultant post construction testing contract. The testing was divided into the following categories:

- Track-to earth resistance for both ballasted and embedded track
- Visual Inspections
- Audio Frequency Testing

The track-to-earth resistance is dependent on the effectiveness of isolators (rail boot, fasteners) and soil resistivity [92]. The increase in the track-to-earth resistance is directly proportional to the isolators controlling the resistance. This is because the soil resistivity varies with temperature and time of the year and is usually not high enough to control stray currents alone. An ideal scenario would be to achieve and maintain a uniform track-to-earth resistance for the entire system.

4.2.2.1 Track-to-Earth Resistance for Ballasted Track

This testing was conducted by impressing a test current, with the help of 12V batteries, at one location along the rails. The track-to-earth voltage shift was then measured at return current spans along the rail at pre-determined locations along the right-of-way. The main purpose for this resistance test is to locate and remove any track work discontinuity prior to the start of revenue service and document the long-term variations in the resistance values [92]. The entire ballasted track length was tested which showed resistance of more than 500Ω/300 track metres. This was set as the target resistance by the contractor. Figure 37 below shows the actual connection at the measuring station.

Figure 37: Track-to-Earth Measurement – Ballasted Track

<u>Result:</u>

No areas of low track-to-earth resistance were identified.

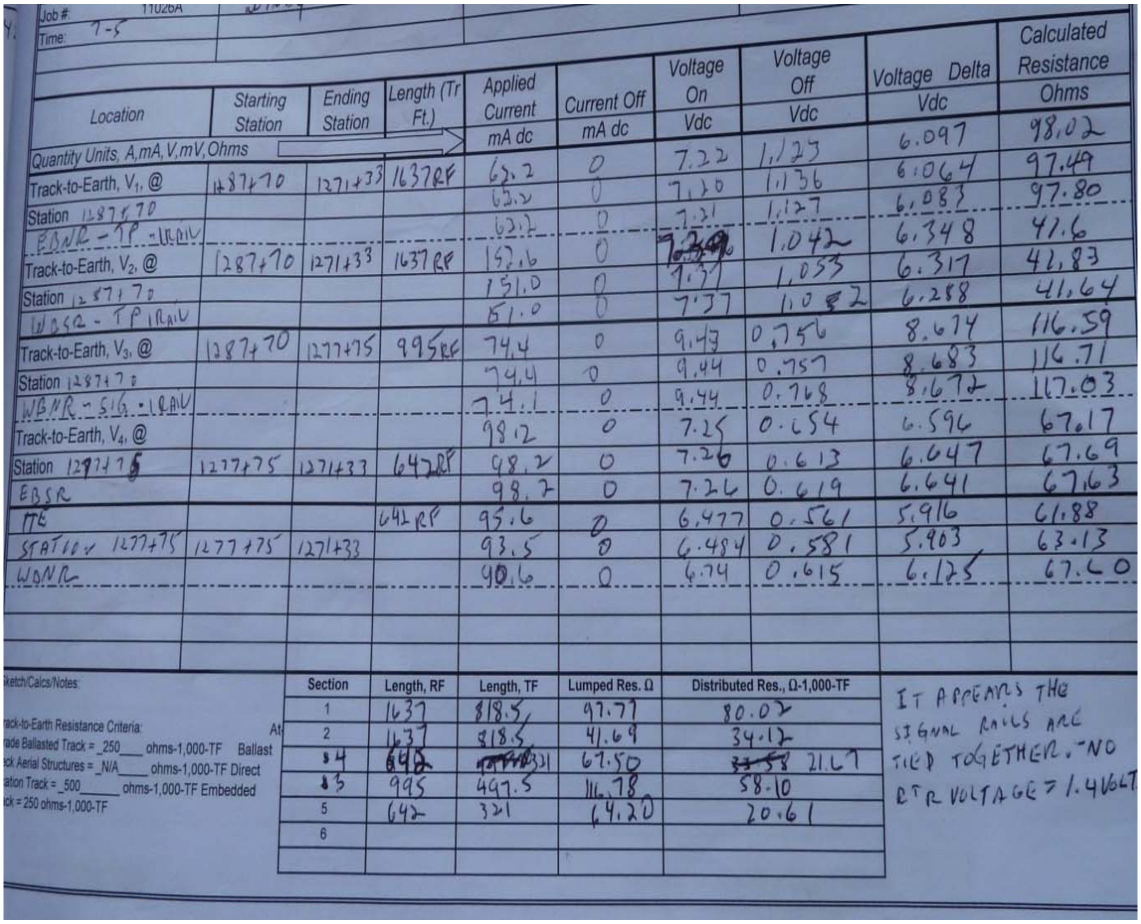
4.2.2.2 Track-to-earth resistance for embedded track

The embedded track testing procedure was the same as the ballasted track where a 12-volt battery was used to impress a test current at one location between the rail and ground while measuring the resistance at another specified location. Five different track locations were tested and none of the locations met the desired limit of 250Ω/300 track metres. The track-to-earth resistance values are typically low in the embedded track since tracks embedded in roadways are in contact with earth. This requires a higher degree of care during construction and later on during maintenance. Figure 38 shows a standard setup for the test.

Figure 38: Track-to-Earth Measurement – Embedded Track

Initially it was assumed that debris (as seen in the Figure 38) and water on the rails on the day of the testing must have caused the significantly lower resistances. The construction contractor was therefore requested to clean the track for a revised testing the next day.

Embedded sections of the track were tested again the next day after the contractor removed the dirt and the concrete spillage over the thin track to earth isolation membrane. However, the track-to-earth resistance results did not improve enough to fall within the transit agency's approved limits. Figure 39 shows some of the test results documented during the resistance testing after the track was cleaned. Figure 39 shows track-to-earth resistance values of less 100Ω/300 track metres.



Job #: 11026A

Time: 7-5

Location	Starting Station	Ending Station	Length (Tr Ft.)	Applied Current mA dc	Current Off mA dc	Voltage On Vdc	Voltage Off Vdc	Voltage Delta Vdc	Calculated Resistance Ohms
Quantity Units, A,mA,V,mV,Ohms									
Track-to-Earth, V_1, @	1287+70	1271+33	1637RF	63.2	0	7.22	1.125	6.097	98.02
Station 1287+70				62.2	0	7.20	1.136	6.064	97.49
EBNR - TP - 1RAIL				62.2	0	7.21	1.127	6.083	97.80
Track-to-Earth, V_2, @	1287+70	1271+33	1637RF	152.6	0	7.39	1.042	6.348	41.6
Station 1287+70				151.0	0	7.37	1.053	6.317	41.83
WBSR - TP RAIL				151.0	0	7.37	1.082	6.288	41.64
Track-to-Earth, V_3, @	1287+70	1277+75	995RF	74.4	0	9.43	0.756	8.674	116.59
Station 1287+70				74.4	0	9.44	0.757	8.683	116.71
WBNR - SIG - 1RAIL				74.1	0	9.44	0.768	8.672	117.03
Track-to-Earth, V_4, @				98.2	0	7.25	0.654	6.596	67.17
Station 1277+75	1277+75	1271+33	642RF	98.2	0	7.26	0.613	6.647	67.69
EBSR				98.2	0	7.26	0.619	6.641	67.63
ITE			642 RF	95.6	0	6.477	0.561	5.916	61.88
STATION 1277+75	1277+75	1271+33		93.5	0	6.484	0.581	5.903	63.13
WBNR				90.6	0	6.74	0.615	6.125	67.60

Sketch/Calcs/Notes:

Track-to-Earth Resistance Criteria:
Grade Ballasted Track = _250___ ohms-1,000-TF Ballast
Track Aerial Structures = _N/A___ ohms-1,000-TF Direct
Station Track = _500_____ ohms-1,000-TF Embedded
Track = 250 ohms-1,000-TF

Section	Length, RF	Length, TF	Lumped Res. Ω	Distributed Res., Ω-1,000-TF
1	1637	818.5	97.77	80.02
2	1637	818.5	41.69	34.12
3 4	642	321	67.50	~~33.58~~ 21.67
4 3	995	497.5	116.78	58.10
5	642	321	64.20	20.61
6				

IT APPEARS THE SIGNAL RAILS ARE TIED TOGETHER. NO ETR VOLTAGE = 1.4VOLT

Figure 39: Embedded Track-to-Earth Resistance Results

<u>Results:</u>

Almost all the sections tested fell below 100Ω/300 track metres and it was concluded that the track needs to be retested after a thorough cleaning from all debris and dirt. This should then be followed by an inspection of the track to spot check any construction flaws like concrete overlaps on the rail boot.

4.2.2.3 Visual Inspections

Visual inspections were conducted in conjunction with the physical measurements taken at all embedded sections to identify any peculiar construction item or impact from other miscellaneous factors at each location. This included walking along the track alignment to monitor for any apparent construction and/or material flaw.

Results:

The inspections identified some concrete overflow over the isolating membrane between the concrete and the rail essentially exposing the tracks to concrete and creating a conductive path. Most of the membrane interface joints were not properly filled with the isolating compound at the surface seam. Additionally, accumulation of dirt and moisture was observed which can cause a potential decrease of the resistance in these areas.

4.2.2.4 Audio Frequency Signal Tracing

An audio frequency detector is used to locate discontinuities in the electrical circuit. The equipment includes an oscillator which converts low voltage (12V) 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 to locate the discontinuities. Where there is a short or discontinuity is observed along the traverse, the voltage suddenly drops to a very low or null level. This is assumed to be a point directly above the contact [90]. In areas where there may be a complicated network of continuous structures it is difficult to pinpoint specific location of circuit discontinuities and other methods may need to be employed.

Audio frequency signal tracing results were used in conjunction with the track-to-earth resistance data to pinpoint local low resistance areas requiring further investigation. These tests were conducted by impressing a 750 Hz signal onto the rail in various configurations and measuring the signal strength along the rails. The testing included surveys at the first test location for the embedded track and showed discontinuity at the crossover where the rail signalling work was in process. Figure 40 shows a typical audio frequency tester.

Figure 40: Audio Frequency Test Setup

<u>Result:</u>

The results identified that the signal loss was occurring at the crossover location. However, since the rail signalling and maintenance crew was working at that location, the test results could not be ascertained accurately.

4.2.3 Conclusion

Of the sections tested for resistance calculations most of the ballasted sections were within the limiting values defined in the transit agency's criteria manual. However, none of the embedded sections passed the test even after cleaning and brushing of the track. One explanation for this was that the embedded section was using a flangeway of concrete which retained earth and debris that in return provided a path for the stray current. This along with the fact that the concrete had spilled over the rail boot at many locations, creating a contact with the rail, annulled the purpose of the rail boot isolation.

Moreover, proper drainage measurements must be taken during construction with careful design considerations for water flow at low elevations and other critical locations. In newer constructions it is recommended to provide a rubber boot flangeway to isolate the rail contact with the earth as shown in Figure 41 below.

Figure 41: Girder Rail with Embedded Rail Boot

The results of the audio frequency identified signal losses at crossover location and close to the signal box including a general signal loss on the tangent track section. It appeared that the signal rails were tied together. The exact linear footage of the track that has a relatively low track-to-earth resistance is short, but since it resides in the measured segment, it affects the reading of the entire segment and re-testing was recommended.

4.3 Summary

One of the critical issues that became apparent is the use of stray current control testing of limiting values by a transit agency. This includes limiting values set forth for slab current, track-to-earth, and pipe to soil testing. Though the transit agencies discussed in this section do define such limiting values, none of them mention the actual soil resistivity testing results conducted to explain/justify the proposed limit recommendations for their system. It is thus inferred that these limiting values that the transit agencies are trying to achieve are based on industry experience rather than on actual soil testing and design parameters of the rail transit agency.

Additionally, it is apparent from tests conducted on the embedded tracks of the above two transit agencies that track-to-earth resistance for the embedded track largely depends on the isolation methods and technique at the time of design, construction and then eventually on the maintenance of the tracks. The key fundamental maintenance essentials to be carried out for ballasted and embedded track system must include:

- Maintain the ballast at a minimum of 2.54 cm. below the bottom of the rails (preferably 5 cm)
- 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

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

- Visual Inspections
- Structure and/or Utility Pipe-to-Soil Potential Measurement
- Track Slab Current Measurement (Ground Current Survey)
- Track-to-Earth Resistance Survey
- Audio Frequency Signal Tracing (where needed)

Testing methods and frequency of testing should be adapted based on the age of the transit system, the location of tracks, the type of the track bed, the type of structure under investigation and the source of leakage.

5 Stray Current Provisions on dc Transit System

Chapter 5 uses the data collected from the literature review and stray current testing observations, coupled with the information gathered from the questionnaire and corrosion consultants' interviews (consultant list is provided in section 3.3) to develop a stepwise process for achieving a uniform stray current isolation and QC for an embedded track.

A significant part of the work described in this chapter provides contribution to original and unprecedented knowledge related to stray current methodology for the guidebook prepared for TCRP. The guidebook is meant to be used by transit agencies, design and maintenance practitioners, and influence new system construction, extensions, and maintenance and operation of existing systems for North American transit agencies. The guidebook includes, for the first time under one cover, 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.

5.1 Uniform Stray Current Isolation Design

Uniform stray current isolation design guidelines coupled with track maintenance and testing programs is a pressing need for the US transit community. This will not only help transit agencies in keeping the stray current leakage to a minimum but will also help in the implementation of QC measures. The implementation of recommendations, best management practices, and pre-planned maintenance regimes come with an initial cost. However, such proactive measures will help reduce the unpredictable and repetitive cost of repair and breakdown in the longer run. This can be observed from the transit agency testing mentioned in Chapter 4 where, with some foresight and proactive planning, redundant construction and testing work could have been avoided.

The information from the literature review, questionnaires, data gathered during the transit agency' interviews, and the data from stray current testing observations was used to create key decision matrices associated with implementing, maintaining, and testing stray current control. Using these matrices, the following proactive sequential steps are defined by the author for the guidance of stray current isolation and QC. These steps include measures that need to be taken pre-construction, during design, and post construction, followed by designed maintenance measures during the revenue service of the transit system. These recommendations, if followed, will ascertain that uniform stray current isolation and QC is achieved for a dc powered transit system.

- Design Essentials
    - Base Line Survey
    - Traction Power Model
    - Track Design
- Stray Current Control
    - Control at Source
    - Isolation Techniques
    - Collection Methods
- Maintenance and Testing Program
    - Coordination
    - Maintenance
    - Testing

5.2 Design Essentials

5.2.1 Baseline Survey

The process of baseline survey from the inception of the transit system plays an essential role in the design of rail transit system and helps develop a proper model for the operation 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 - including resistivity tests, pH tests, sulphate content, and chloride content tests. Soil corrosion characteristics like resistivity, pH, sulphate content, and chloride content are used to determine CP needs, cement types for concrete, coatings for structures, and ground bed and grounding grid design.

- Atmospheric corrosion characteristic - this includes, 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 in the vicinity of the rail line. Initial surveys should be conducted to find out the utility and other metallic infrastructure in the vicinity of the rail line.
- Education and Participation - Educating the relevant transit agency staff, and other key stake holders, on stray current corrosion and reaching out to local corrosion societies.
- Develop a Risk Matrix for existing and potential corrosion issues

Most of the baseline survey element data gathering involves a survey of the surrounding infrastructure, educating the transit agency staff, and coordination with the utility owners. Soil resistivity and its testing is an important component of the baseline survey that requires special attention and assists 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 deliberated in detail throughout this thesis.

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 the 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 skipped before the 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. It should be noted that revenue service creates dynamic conditions that render confirmation of compliance challenging and thus testing in such conditions has its drawbacks. Additionally, stray current leakage has been found to be difficult to achieve after a system has been in service for a few years.

Like any other design/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 a LRT/HRT design project is equally important. However, without the baseline survey data there is no source data/findings to compare the testing results against.

5.2.1.1 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 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 TPS's.

The measurement procedures should follow the following industry standards:

- ASTM G-51-77 (for pH of Soil for Use in Corrosion Testing)
- ASTM G-57 (Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method, Annual Book of ASTM Standards)
- ASTM D-1557 (for Moisture-Density Relations of Soils and Soil-Aggregate, Mixtures Using 4.5kg. Rammer and 46cm Drop)
- ASTM G 165 (for Rail-to-Earth Resistance measurement)
- NACE, Control of Pipeline Corrosion, A. W. Peabody, Soil Resistivity Measurements and Data Evaluation

- IEEE STD 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 US 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 on the grounding topography [93].

A typical soil resistivity study would include measurement locations at 150 m spacings and at depths of 0.75, 1.5, 2.3, 3, and 4.5 metres. A Barnes layer analysis 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 analysed 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 typically selected to cover a wide range of soils along the ROW.

The selected soil resistivity level can be used to 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 of the order of 75 millivolts over a 300 m earth span perpendicular to the rails. Variations in this parameter are used to simulate various conditions such as close proximity utility structures, long crossing or paralleling pipelines. The allowable stray current level determined in this phase of the design will be compared to the Traction Power Load Flow Model to calculate the required track-to-earth resistance levels.

5.2.1.2 Atmospheric Corrosion Characteristic

Climatological conditions comprise gathering of local weather data including but not limited to temperature, relative humidity, and precipitation. Air Quality data of local area constitutes determination of local area pollutants and their concentration in comparison to the appropriate local Air Quality Standards. This data should be collated using a matrix format and analysed in an interpretive report to validate their influence on corrosion of the rail infrastructure.

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

5.2.1.3 Surrounding Infrastructure and Utility Location Survey and Coordination

Maintaining effective communications 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 the 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 stray current survey should include the following:

- 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.
- The stray current potential (voltage) measurements should be recorded for all the utility structures within the proposed project boundary including the vicinity of

maintenance and yard facilities, using copper-copper sulphate (Cu/CuSO4) half-cell reference electrode which serves as a reference point to ground.

- The structure-to-earth potentials should be recorded for at least 24 hours at 2 second intervals at each recording location.
- Record at least 2 minutes of recordings at 2 millisecond intervals in order to confirm if there is significant mains-frequency voltage or other higher frequency components present at each recording location.
- The recorded data should be taken over approximately equally spaced locations (91 m – 150 m) and at critical utility crossing locations within the proposed project boundary.
- The utilities that have cathodic protection need to be identified and further designated 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 regular basis

5.2.1.4 Education and Participation

Another aspect that was realized during the research is the need and importance of having 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 their staff is trained on the fundamentals of stray current. 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 the rail track.

Participation in the current local corrosion committees that exist and/or in any stakeholder engagements should be carried out. This would help in being aware 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 the 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.

5.2.1.5 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 of all project specific components both within and outside the project boundary which are at risk from stray currents from the dc transit system. This is based on survey results and means of protection for each asset, and will be maintained in a risk register that details all assets at risk from stray current
- Identification of any residual stray current.

5.2.2 Traction Power Model

The design of a transit system requires an understanding of the transit system demand. Commercially available professional simulation models are typically used for the design of traction power. These simulation models provide and help optimize the multi vehicle movement and performance, traction power average and peak performance, and substation loading characteristics and distances [94]. A corrosion engineer then uses this traction modelling data to calculate stray current leakages including track-to-earth resistance. This requires an early coordination between the traction power designer and the corrosion engineer.

5.2.3 Track Design

Embedded track designs require a more complex level of electrical isolation compared to ballasted tracks and thus demand an early contribution from the corrosion engineer. Following are some of the key elements of the track design that must be cross checked with the corrosion engineer at an early design level to avoid potential short and long-term stray current leakage issues:

- Drainage at and around the tracks
- Rail boot construction (the joints in particular)
- Grade crossings
- Insulating fasteners
- Special construction like bathtub isolation
- Plastic, concrete, or wood ties
- Isolation of storage and maintenance yards

5.3 Stray Current Control

Depending on the baseline survey findings and during the design of a dc powered rail transit system, steps must be taken to incorporate stray current controls. Based on the literature research and verified through actual survey and testing of transit agencies in earlier portions of this thesis, stray current control should start with the notion of "control at source". This should subsequently be followed by mitigation of the stray current, the collection of stray current leakage, and then finally the ongoing planned maintenance and testing of the tracks. Table 13 lists the measures adopted for stray current control.

Table 13: Stray Current Control Recommendations

Stray Current Control	Recommended Methods
Control at Source	• Floating/ Ungrounded system • Design of traction supply circuits with low resistance • Design of traction return circuits with high resistance • Increasing the cross-sectional area/size of the rail (90-120lbs., 40-80 mΩ/km) • Maintaining a continuous electrical path for the negative current by using continuously welded rails. • Isolation of yards and storage areas • Frequent cross bonding (76 m - 150 m) • Substation spacing (< 1.6km or between > 1.6km and < 3.2km) • Insulated fastener clips • 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). • Use of elastomeric rail boot. • Filling the entire trough of the embedded rail with dielectric polyurethane or combination of other suitable material (like cork or polyurethane). • Insulating the anchor bolts that penetrate beyond the insulated rail trough. • Provide metal or fibre reinforced U-shaped boxes for the rail trough with cork spacers to align the rail and fill the gaps in the trough. • Use of high resistivity concrete mixes using mineral admixtures (this can also be part of mitigation measure)
Mitigation	• CP (Sacrificial anodes) • Drainage bond (In rare scenario when other alternatives cannot be used)
Collection	• Steel collection mat along with the collection wire

The applicability of the above-mentioned techniques vary on a case by case basis and their individual or combined use is largely dependent on the environment and location of the embedded tracks within the transit system.

5.3.1 Rail Sections and Rail Boot Applications

As far as rubber rail boots are concerned, there are two different applications for the tee rail (Figure 42 & Figure 43); one where the flangeway is constructed of grooved concrete and the other where the application includes the rubber boot to snap on to the flangeway section (creating a grooved section). The later application, which is the preferred one, addresses the problem of dirt and debris being collected in the concrete flangeway because such dirt and debris provides a conductive route for the 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 at the site along with other secondary joining materials. Depending on the boot manufacturer, the secondary materials 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 [89].

Figure 42: Tee Rail with Grooved Rail Boot

Figure 43: Tee Rail with Rail Boot and Concrete Groove

Research has shown that the rail boot provides very good insulation when first installed, but with time, weather variations, standing water, and rail traffic, it inevitably undergoes wear and tear thus allowing stray current leakage. 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 stray current control.

Special attention is also warranted for the proper placing of the rail boot and the subsequent concrete pour around it during construction. If not done meticulously, there have been instances where the track has failed the safety test and the boot has needed 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. Using the simulation model developed as part of this thesis, increased deviations in stray current leakage due to the degradation of rail-to-earth resistance are presented in section 6.6.5, Chapter 6. The results from these simulation models validates the importance of maintaining the rail-to-earth resistance to designed values.

5.3.2 Stray Current Collection

In high traffic urban areas and 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. There are situations where mitigation measures must be augmented by the use of collection systems (like steel collection mats). These collection mats are laid on concrete slabs with steel reinforcement, such as in tunnels and viaducts, to intercept and retain stray currents from embedded track sections. In such instances a stray current collection mat, in the concrete below the tracks, provides a low resistance path to intercept and retain 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 be directly connected to the mat at a regular interval (100 to 300m) 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.

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, stray current collection systems with a high efficiency are more challenging to achieve. In such cases, it may be more economical to consider other ways to reduce stray current level at the source, such as insulating the entire trough that carries the rails and the use of 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 more detailed analysis and design is required to control the impact of stray currents on these structures. Using the simulation model developed for a basic floating transit system, with substations at each end and a train in the middle of the track, the impact on the overall stray current leakage with and without collection mat is shown in section 6.6.4, Chapter 6.

5.4 Maintenance and Testing Program

It is important to conduct regular periodic inspection 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 a very important component to the success of a robust maintenance and testing program.

5.4.1 Coordination and Communication

The development of a coordinated effort to sustain effective stray current control requires education, communication and cooperation of all stakeholders and concerned parties. Communication is the foundation of the effort to achieve and maintain effective stray current control. Thus, it is essential that regular exchange of information be maintained between the interested parties to develop an overall sustainability of effective and efficient stray current control. As presented in Chapter 4, COH and METRO both carry out pipe-to-soil potential measurements on the water lines that cross the light rail tracks in Houston. This redundant testing is a costly and inefficient duplication of efforts which can be avoided if such two entities would coordinate and collaborate beforehand to ascertain that one consultant is hired to conduct the testing and implement subsequent mitigation measures, if needed.

5.4.2 Maintenance

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, due to heavy wear and tear in urban surroundings coupled with the periodic maintenance required to track systems, rail rubber boots inevitably end up getting damaged. This unpreventable wear and tear warrants regular maintenance to be an essential element of the stray current control regime. Fundamental maintenance essentials for embedded track system must include:

- Maintain rail isolation from all metal objects
- Maintain clean and dry tracks (control vegetation)
- Perform regularly scheduled visual inspection of the tracks
- Maintain CWR 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 44 shows an example of maintenance work at a light rail 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, a polyurethane compound by the name of iso-flex was used to provide the required non-conductive membrane between the rail and the ground [95]. Due to higher cost of this polyurethane compound it is only used to repair smaller sections.

Figure 44: Iso-Flex Replacing Rail Boot

5.4.3 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 corrosion issues caused by the stray current early on and then would help in mitigating those corrosion problems based on the data gathered from such testing.

Research, literature review, and transit agency personnel feedback highlight the need to test the entire transit system at least once every three years on newer systems and once every one to two years for older systems. The following tests are recommended to be performed based on the type, size, and physical environment of the system:

- Structure and/or Pipe-to-Soil Potential Measurement
- Track Slab Current Measurement (Ground Current Survey)
- Track-to-Earth Resistance Survey
- Audio Frequency Signal Tracing (where required)

Worth documenting here is the fact that out of the transit agencies surveyed, questioned, and tested as part of this thesis, only a handful currently perform such regular testing of the tracks. It was discernible from the results of the survey questionnaire that these agencies have less stray current problems.

5.5 Summary

For embedded tracks the design must have an electrical barrier to insulate the rail from the conductive parts which have the potential of carrying the current to earth. Even though bituminous asphalt and different mixes of concrete embedment [95, 96] have been used in the track design in combination with other epoxies, the rail boot has been proven to be the most effective and cost efficient stray current control measure. The rail boot not only provides vibration isolation, but it also buffers the rail and its supports from the surrounding structure, thereby providing resistivity to stray currents leaving the rail. It thus protects not only the rail but also the surrounding infrastructure from corrosion. Some of the key benefits of the rail boot are mentioned below:

- Quick and easy installation without the need of 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 avoided.
- Rubber boot track system is simple to construct.
- Minimal maintenance of paved track system as compared to other techniques.

A factor that has been found to contribute to stray current leakage is the inconsistent design of extensions of an existing system. The extension of an existing system can result in the increase of stray current leakage except when the older track is electrically isolated from the new track or is designed for similar or as stringent stray current control as the new track. An example of this was witnessed during a survey of a transit system in the east coast, where the older track was improved by the addition of closely spaced substations to reduce the stray current effects from the new extension.

In conclusion it would be easier to implement most of the above-mentioned isolation, mitigation, and collection options on a newer transit system with proper foresight and planning. However, not all the options and recommendations discussed in this section will apply to older systems or systems that are building extensions to their existing systems. In such instances it will be the responsibility of the design engineer/consultant in consensus with the transit agency/owner to design the system that will keep the stray current corrosion to a minimum. 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.

6 Modelling

The process of stray current design starts with the design of the transit system which requires understanding the transit system demand. This chapter briefly discusses the simulation modelling for traction power design and its consequences for the control of stray current leakage and stray current modelling.

Power supply in a dc transit system can be classified into positive and negative circuit networks. The rectifier at the substation provides power to the train, whereas the train is modelled as a current source. The power changes in both the rectifier and the train as a function of time. The positive circuit runs from the rectifier at a substation through the conductor rail or overhead catenary, whereas the negative circuit includes the running rails, and the stray-current collection system (if employed). As a result, stray current and rail potential are events that belong to the negative circuit network.

Stray current, in the negative circuit network of a dc transit system, will follow the path of least resistance on its way to the substation. This can cause significant corrosion to the metallic structures where it leaves the conductor, which includes rail, its components, and other metal infrastructure in the vicinity. Measures therefore need to be taken to contain stray current at the source by providing suitable insulation and/or by using other means of rail isolation and current collection. Pertinent stray current control measures can only be implemented when a fair assessment of stray current leakage is conducted. This evaluation of stray current starts at the transit system design level (pre-construction) and is followed through by regular maintenance and testing of the transit system.

A computer-based simulation model was developed in Fortran, by the author, using a nodal analysis method and commercially available Zollenkopf bi-factorization algorithms to detail the return circuit for the calculation of rail potential in a floating dc transit system. The model was tested on simple traction power networks to explain the variation in rail potential and stray current due to the changes in design and input parameters including rail resistivity, substation spacing, cross bonding, and rail-to-earth resistance.

6.1 Traction Power Models

Traction power simulation models help to optimize multi vehicle movement and performance, traction power averages and peak performance, and substation loading characteristics and distances [94]. Since stray current leakage and its corresponding mitigation design is influenced by the chosen design of the above parameters, it is imperative to establish an early coordination between the traction power designer and the corrosion engineer. This process would benefit from achieving a sensible and comprehensive design including the selection of earthing systems for the transit system. Typically, corrosion engineers make use of the results from the traction modelling to calculate the stray current leakages to achieve an optimum design.

Regardless of the simulation model being used, the main input required for the simulation of traction power includes the following data:

- Infrastructure
- Power System
- Rolling Stock
- Signalling and Control
- Vehicle Timetable

Based on the operational timetable two main simulation scenarios, normal and emergency feeding conditions, are usually analysed to assess the capacity of the traction power system. As the name suggests, a normal feeding condition is simulated with all traction power substations and feeding locations in service. Whereas emergency feeding conditions are modelled using different power outage conditions. Traction power substation locations, feeding arrangements, train power consumption and performance requirements are designed and evaluated from the analysis of these simulation results. These elements are an essential component of the load flow study.

For the purpose of this thesis and to help facilitate the input data for the modelling work, actual traction power simulation results from commercially available VISION®/OSLO® traction power simulation software were used. The stray current simulation input data was further supplemented with real world client preferences, project criteria and data from an existing consultant project. This project includes extension of an existing line.

The train movement simulator VISION® (Visualization and Interactive Simulation of Infrastructure and Operations on railway Networks) considers the dynamics of train motion at regular time intervals and returns a power demand for each train in the network. The traction power network simulator OSLO® (Overhead System Loading) is overlain on the VISION® movement model which provides comprehensive mathematical modelling of the traction power network and its equipment. The two models interact with each other to provide values of tractive effort (force/energy to move the train), line current, and train voltage that are compatible with the traction characteristics after going through an iterative procedure [94]. These calculated values of line current and train voltage are then used for further analysis and design of stray current. For the purpose of this thesis the train voltage and line current values calculated as part of the real-life transit project are used in the stray current simulation model in section 7.1 to attain the maximum stray current potential, total stray current leakage and metal loss.

6.2 Basic System

In dc electrified systems; the return current leaks into the earth where the rail potential is positive with respect to remote earth (stray current). This leakage current is defined as stray current and can be recorded and obtained for every instant of time, by monitoring the total stray currents using a function of total stray current against time. The gross leakage charge is obtained by integrating the total stray currents against time as shown in the equation below [27].

$$Q = \int_{t1}^{t2} i(t)\, dt \qquad (23)$$

Modelling carried out here and in the subsequent chapter is based on the principles and theory as described below. Figure 45 shows a 1-km section of track used to illustrate the rail-to-earth voltage profile and stray current for a symmetrical 2-km section of a track with a train in the centre of the track. This train draws a 1000A current that has been produced by the substation shown at the far-end of the track.

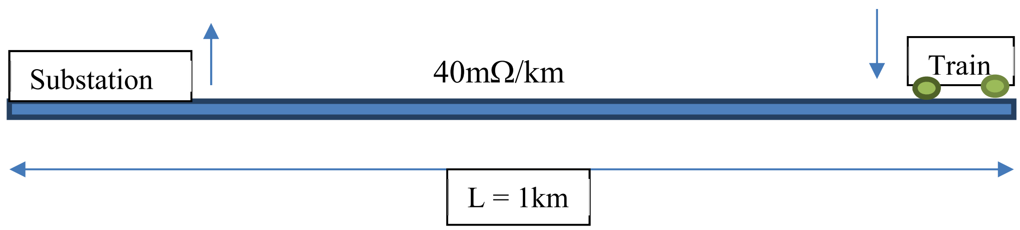


Figure 45: Section of Track to Demonstrate Stray Current Production

For a section length of 1-km, rail resistance of 40mΩ/km (20mΩ/km for two rails), and a train current of 1000A, the resulting voltage difference between the two ends of the above section of track is calculated to be 20V. For a floating system, where the rails are not grounded, this voltage will show 10V near the train and -10V to remote earth near the substation as shown in Figure 46. This means where the voltage is positive (at train location) the current leaks out of the rails into the earth due to the finite resistance of the rail and becomes stray current. The current then jumps back onto the rails where the voltage is negative (at substation location). This is explained in Figure 46 where the stray current leaves the rail in the region of 500m-1km and re-enters the rails in the region of 0-500m. Values of voltage to remote earth at any point along the track and track-to-earth resistance are used to determine the magnitude of current leaking from the rails.

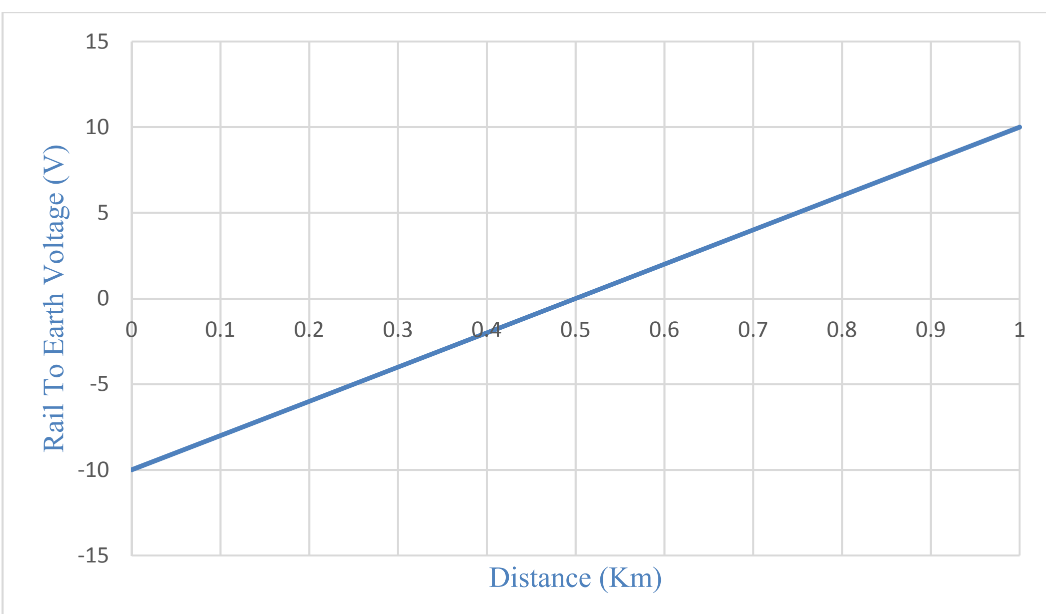


Figure 46: Rail-to-Earth Voltage for Floating Earthing System

Further assuming that this 1km section has a rail-to-earth resistance of 500Ω/km and that the current will return via the return rails, the "resistance to earth" is calculated as 2000 Ω. Making use of Ohm's law, the previously calculated rail-to-earth resistance, and the voltage (10V), the stray current (leakage current) is calculated to be 2.5mA. Using the approach mentioned here, the magnitude of the current leaking from the rails can be determined by the voltage to remote earth at any point along the track for the given resistance to earth. Stray current density can also be calculated and the leakage density can be expressed in mA/m that is the stray current leaving per 1m section of rail.

In bonded rail systems, where the running rails are effectively bonded to earth at the substation, the leakage pattern is different. The voltage will appear on the rails as 20V to remote earth at the train and 0V to remote earth at the substation. Thus, the voltage is always positive with respect to the earth and the stray current will leave the rails along the entire length of the track, returning to the rails at the substation where the rails are grounded. This results in additional stray current leakage and thus confirms floating systems as the preferred system. This conclusion is shared by multiple other researchers [26, 27, 37].

6.3 Stray Current Modelling Principle

The main objective of this chapter is to discuss stray current modelling principles and techniques, and to perform modelling to calculate stray current and metal loss to utilities using the dc transit system data. Stray currents are hard to detect as they vary with the dynamic rail traffic. Computer based simulation models have been used for over two decades to calculate the current leakage and its potential impact on dc rail transit system and neighbouring infrastructure.

The modelling carried out here is based on resistive networks which are solved using the nodal voltage circuit analysis, by means of algebra, as presented by other researchers [39, 71 – 73]. The traction system components; return circuit and traction supply are broken down into a number of longitudinal sections called finite cells, of equal length, which constitute a series resistance R of the rail and shunt leakage conductance G. These components are modelled in terms of resistances, and of current sources, the interconnection of which constitutes a nodal electrical circuit. A track is presumed to consist of two similar rails in parallel resulting in half the longitudinal resistance of a single rail and values of R and G vary for each section along the rail.

The relationship between the network conductance, voltage and current can be obtained by using matrix algebra to solve the simultaneous equations and can be represented by the following equations:

$$I = G \times V \qquad (24)$$

$$V = G^{-1} \times I \qquad (25)$$

Equation 24 is the basic equation whereas equation 25 is used to solve for nodal voltage derived using the inverse conductivity matrix. Where *G = n x n symmetrical nodal conductance matrix, n = number of nodes, I = nodal currents (all zero except substation nodes), V = Nodal voltage*

As shown in Figure 47 the system model for the track is in the form of a ladder which are interconnected at substations, paralleling points (also referred to as paralleling stations), and cross bonds. The modelling is designed to take into account scenarios where paralleling stations (where the overhead conductors or third rails of the two tracks are connected together) are used to improve power distribution.

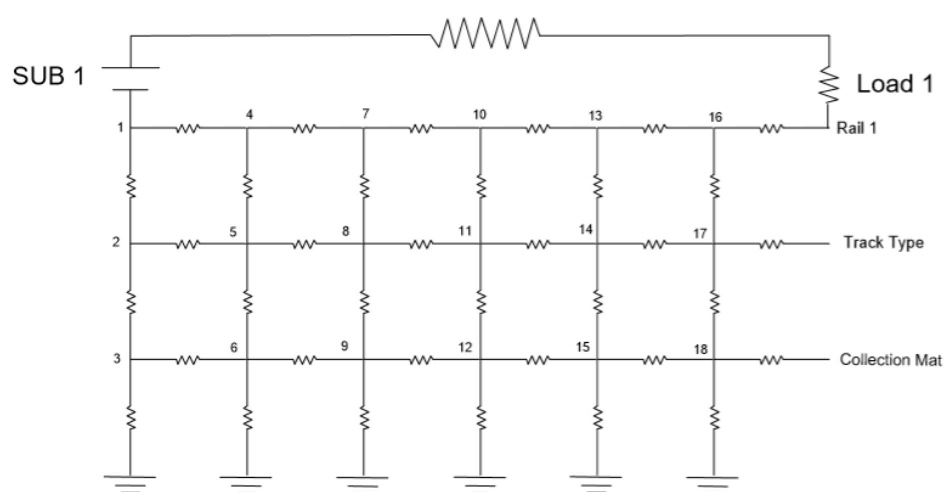


Figure 47: Typical Nodal Sketch

The input file used to establish the circuit model defines the system parameters including the location of the traction elements (trains, substation, paralleling stations, and cross bonds). Nodes are then sequenced in a logical way to facilitate additional manipulation. A cell length of 100 m is considered sufficient for the modelling of dc transit systems, however, the length of the cell can be changed to higher and lower values depending on the complexity of the actual system. Keeping the node lengths at 100m or higher keeps the number of equations under check and provides iteration within reasonable time. The branch conductance and end node numbers of branches along the rail and branches between substation positive and negative busbar locations are also used as input in the program.

Using these finite cells and the principle of nodal analysis, a complex network that can handle multi-branched lines and can incorporate return circuits has been modelled in Fortran as part of this thesis. To minimize the computation errors and in order to not compromise the accuracy of the modelling process, smaller length cells and a single branch line is used. Once the node and branch data have been identified, the model then employs the Zollenkopf's bi-factorization algorithm [97] for solving the nodal voltage equations. This bi-factorization method forms a sequence of elementary matrices from the original matrix and forms an inverse matrix by multiplying these matrices together. However, before the bi-factorization starts, an elimination sequence process is undertaken which produces data structures required to hold the elimination factor matrices. The elimination step incorporated here identifies and stores nonzero elements. Train, substation voltages and currents are obtained by successive matrix multiplications which are then used to calculate rail potential and associated stray current along the route based upon the trains location and power demand.

The model is constructed with logical functions and decision-making loops with the capability to process large number of principal nodes and aids in generating the resistive network automatically. The input file can be modified to select discrete locations of train, substations, parallel stations, and load capacity to analyse different location and load conditions. Figure 48 illustrates the basic logical sequence of the stray current modelling process.

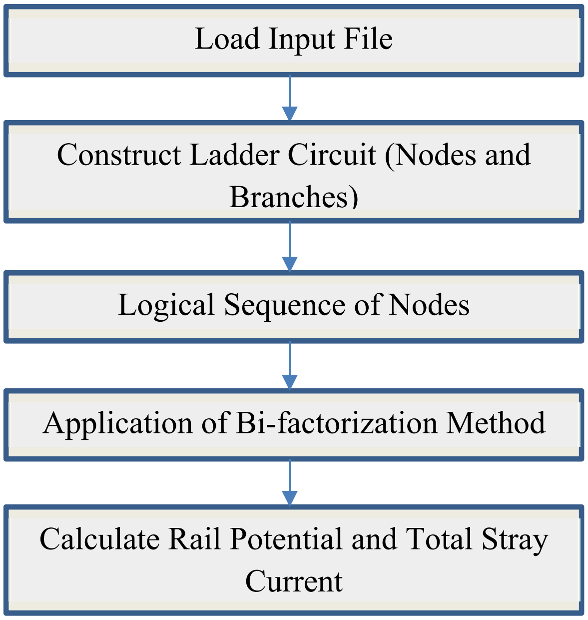


Figure 48: Logical Sequence of the Modelling Process

The fundamental philosophy of the model is to calculate rail potential at the defined nodes of the resistive network using transit system design parameters and to provide the total stray current. Additionally, the rail voltage profile calculated at each node is used to calculate stray current at that node location. The total stray current is calculated by adding the individual stray current values at each node.

The results from the stray current simulation model were compared, and are presented in section 6.4, with the numerical method mentioned in the BS EN 50122-2:2010 annex C [65] using a floating rail section of 1km length.

The literature research suggests that floating earthing system and running rail is the best option to minimize the stray currents [24, 26]. Since in a floating system the running rails are not grounded to earth, they do not have a specific reference to the earth at the substation. Therefore, a simulation model is designed to evaluate the floating system and the results of the model are explained in later sections. The model can be amended, in future, to assess the effects of diode earthing system.

With this modelling approach the effect of cross bonding of tracks, rail-to-earth resistance, substation voltage, and substation spacing on the stray current level produced by the system can be critically analysed. The model also includes an option to select the stray current control collection mat which is designed to capture a major proportion of the stray current released by the running rail. This collection mat when used, protects the third party buried infrastructure in proximity to the dc transit system.

The total stray current and the rail potential calculated for a dc transit system gives an indication of the magnitude of metal loss and corrosion risk. However, in order to assess the metal loss accurately, a more detailed analysis and modelling needs to be carried out which is discussed in later sections of this Chapter.

6.4 Validation of the Stray Current Model

6.4.1 Numerical Validation

When associating the outcomes of stray current leakage calculated using the simulation model with any numerical method, care must be taken in interpreting the results. For example, using the equation in BS EN 50122-2:2010 annex C [65] for a floating rail section 1km long with a rail resistance of 40mΩ/km, traction current of 2000A and rail-to-earth resistance of 100Ω/km the maximum stray current is calculated as I_{stray} of 50mA when the train is at 0.5km. As mentioned in the BS EN 50122-2:2010 code these calculated values may be higher than in real life and a more detailed calculation should be used if the values are higher than 2.5mA/m per single track.

In contrast to the BS EN code mentioned above, the simulation model assumes two parallel tracks and provides the aggregate of stray current value along the length of the track instead of the maximum positive stray current of a section. Using the same input parameters, the model is designed to calculate rail potential at nodes that are spaced at a distance of 250 m (a total of seven nodes including substation and train load location). The stray current at these nodes is determined by multiplying the rail potential calculated by the model with the conductance of the running rail with respect to earth. Figure 49 shows the stray current profile. Although the maximum stray current under the train load is 31.5mA, the total aggregate stray current of the system is calculated as 50mA from 0-1km by the simulation model (represented by the shaded area in Figure 49). This stray current value matches with the stray current results obtained using BS EN code.

Additionally, the model can take into account the voltage of the line and the substation positive and negative feeders, varying substation spacing, and parallel tracks. This gives a more realistic idea of the stray current leaving the rails along the length of the track.

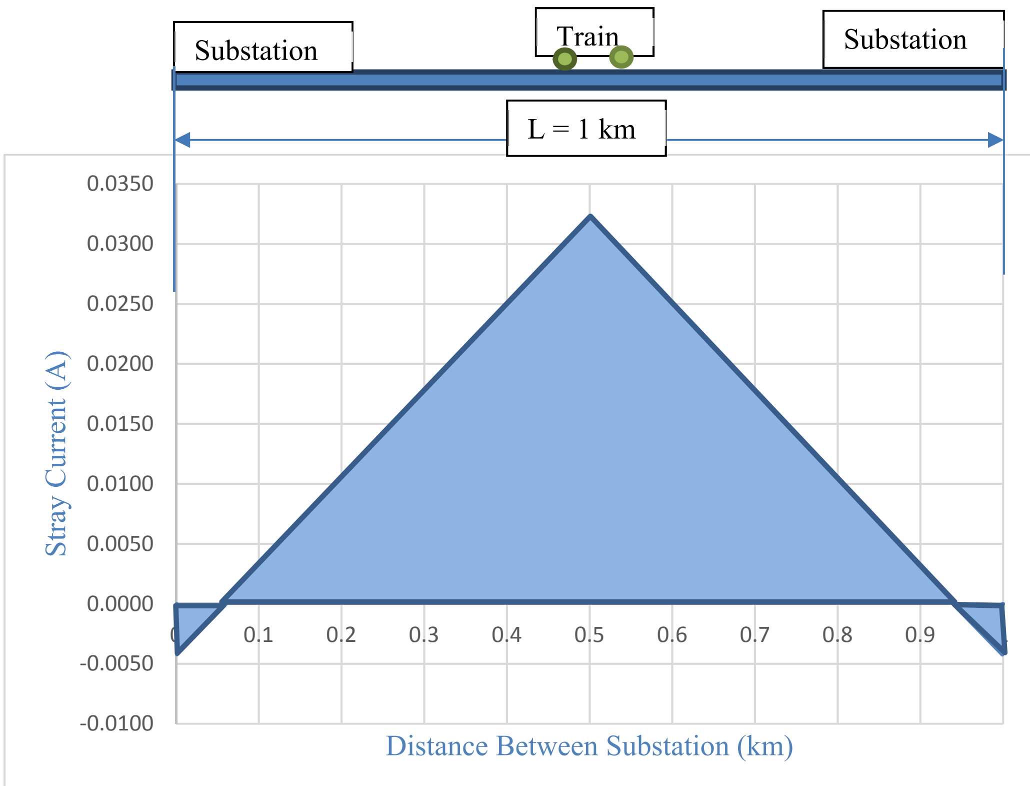


Figure 49: Stray Current Model – Numerical Validation for Floating System

6.4.2 Scaling Factors for Varying Current Conditions

Varying the traction current will influence the leakage current due to the resulting variation in the rail-to-earth potential. Doubling the track current will lead to an increase in the voltage (double to previous value) and thus an increase in the stray current. This is a linear effect where the two parameters, track current and rail voltage, are directly proportional to each other. This is proven by using the two current values provided in the table below and running the numerical method and the simulation model twice.

Thus, the stray current level for real life projects can also be achieved by applying the scaling factors to the results. Table 14 demonstrates and compares the results of stray current leakage for varying track current to double the amount which results in doubling the voltage and thus the stray current.

Table 14: Stray Current Results Using Code and Simulation Model

Traction Current	BS EN 50122-2	Model
Stray Current when I = 2000A	50mA	50.22mA
Stray Current when I = 4000A	100mA	100.45mA

The scaling factor, however, is applicable to systems with similar substation spacing and is not applicable while calculating the potential stray current leakage for varying substation spacing. To that effect the simulation model can handle varying substation spacing.

6.5 Utility Corrosion Risk and Metal Loss

Stray current causes a difference in electrical potential between a metal (pipe) and the soil. Corrosion in the metal pipes occurs when stray current leaves the metal pipe to return to the substation through the soil. Various methods have been designed and used in the past by utility owners to limit and/or eliminate the corrosion risk to pipes. These include the use of select backfill, concrete coatings, cathodic protection, sacrificial coatings, rust protective coatings, paints, zinc coatings, polyethylene encasement, and a combination of these techniques. All these techniques result in a more expensive product. In spite of these measures, metal pipes are still susceptible to corrosion since no coating is defect free. Moreover, during installation and construction the coating may be subject to scratching thus exposing the pipe to corrosion.

In an ungrounded dc transit system, the intensity and flow direction of stray current changes continuously and so does the pipe-soil potential. Thus, if not managed and mitigated properly, it increases the utility corrosion risk. A study carried out by Zhang et al [98] monitors the continuous stray current by measuring the pipe to soil potential of a gas pipe using virtual instruments on an actual system. The results of the study demonstrate a possibility of serious stray current corrosion and suggest that protective measures should be taken to control stray current and to minimize the corrosion risk.

BS EN 50122-2:2010 – BSI, recommends an allowable level for stray current to be maintained per unit length (2.5mA/m) based on the assessment of stray current during the design stages. It recommends conducting a detailed assessment of the risk due to stray current, if the initial assessed value of stray current exceeds 2.5mA/m. The code further anticipates no corrosion damage on the tracks over a period of 25 years if the average current per unit length does not exceeds 2.5mA/m [65].

In general industry practice, the intensity of stray current is calculated by measuring the potential of utility pipeline [99]. This is a post construction approach which assumes that the stray current measures in place are effective and the infrastructure to be constructed is protected. The same approach is taken for existing infrastructure for older transit systems.

Determining the corrosion risk to a metallic utility pipeline is a complicated task and dependents on various variables. These include but are not limited to:

- Location of the pipeline with respect to the rail (Horizontal and Vertical distance, Orientation angle)
- Amount of current flow
- Area and size relationship
- Resistivity of the electrolyte (soil resistivity)
- Electrochemical response of the utility pipeline
- Contact resistance (this is the resistance between the pipe and the soil).
- Coating of the pipe (if coated)
- Environmental factors like; temperature, moisture, ion concentration (like presence of aluminium etc.), electron concentration in the soil, pH of soil

A study by Andrade et al [100] presents a contactless model which calculates the corrosion rate by electrostatically polarizing the metal. This method utilizes an external electrical field to induce an electrical current in the model. The model assumes that current runs in parallel through the electrolyte and the metal is polarized without having a direct physical contact. The polarization resistance, Rp is defined as

$$R_p = (CE / CI) \qquad (26)$$

Where the current density, i_{corr} is calculated as:

$$i_{corr} = B/R_p \qquad (27)$$

Where C defines the change in potential and current, and B is a constant between 13 and 52 mV, depending on the type of metal and its electrochemical condition [100].

A later study by Fichera et al compares the results of the stray current calculated from the above model to a lumped parameter simulation model [101]. Without sacrificing the accuracy, the lumped model includes the modelling of discontinuities by introducing complicated situations like inclusion of local defects in rail fasteners, the soil layers, and the buried metallic structures. The model calculates the stray current in a uniform soil or multilayer soil with no buried metallic structures.

6.6 Evaluation of Simulation Model

The type and size of rails (rail resistivity), type and size of track, rail-to-earth resistance, cross bonding, and substation spacing are some of the key elements of the transit system that dictate the extent of stray current leakage and systems performance. With careful track design and perfect insulation around the rails, any level of rail voltage could be tolerated with minimal stray current effects (though touch voltages may become an issue). In actual practice though this does not happen, and the insulation starts to crack/break after a few years. Thus, the control at source needs to be supplemented by stray current collection and mitigation methods. The leakage of stray current needs to be assessed from the very inception of the transit system design and having the right simulation model will help attain the optimum design.

The modeling presented in this section is based on actual design parameters that are taken from a real-life transit system project with two parallel tracks. Some of these parameters are then modified to create different scenarios to compare the effects on the rail potential and resulting stray current. This section represents a simple static model in Fortran (developed by the author) where the train is running at a constant velocity along a 2km section of track while drawing a constant current of 1000A (current is amplified to better present the stray current impact).

The simulation model calculates the rail potential along the length of the track which is then used to determine the amount of stray current leakage. By monitoring the total stray current (i.e. current leaking off a metallic structure) during each time step of the simulation, the total corrosive stray current can be obtained for varying substation spacing, rail resistivity, and cross bond spacing scenarios.

6.6.1 Substation Spacing

This section provides the results of the simulation model based on different substation spacing along the track. For the initial case study, a single substation is considered at 0km, at the beginning of the track. For the second case study substations are considered at each end of the track, at 0km and 2km. For the third and final case study only one substation at 2km, at the end of the track is considered. The train is considered to be on track 1 and the two tracks are cross bonded to each other. Table 15 illustrates the detail of the model and its input parameters. Figure 50 illustrates the rail potential produced for the different scenarios.

Table 15: Substation Design Parameters

Parameters	Details
Length of Track	2km
Number of Substation	2 (second case study)
Train Location	1km
Substation Resistance	0.06Ω
Train Current	1000A
Rail Resistance	0.06Ω/km
Cross Bonding	1 @ centre of track

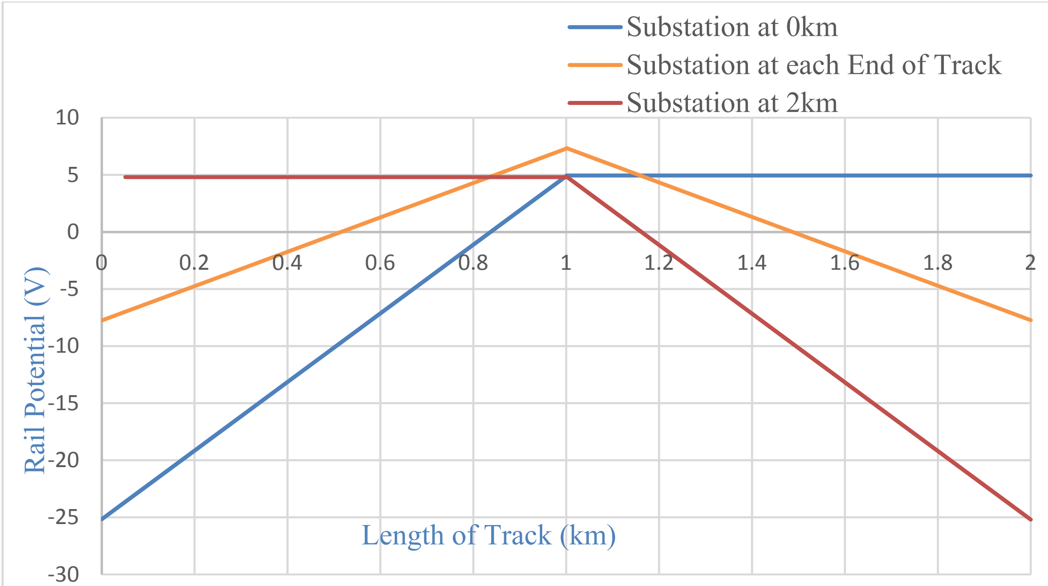


Figure 50: Effect of Substation Location on Rail Potential in Floating System

The results are broadly in line with expectations, the explanation provided in section 6.2 and the literature review. The model provides rail potential along the length of the track. Figure 50 shows that the voltage is positive at the train location and negative to remote earth at the substations, for a floating system. Using closer substation spacing in the simulation model for a floating system not only validates the assertion stated above but also authenticates the stray current control measure, defined in Section 5.2, that closely spaced substations result in less stray current leakage. Overall, there is less stray current along the rail for the case study with two substations due to the shorter return current path. This demonstrates that reduction of the feeding distance reduces the rail potential.

It is also clear from the results presented in Figure 50 that for scenarios when the substation is only at one end of the track, the positive potential (5V; which represents stray current leakage) stays constant for the remaining length of the track in the direction of no substation. When the substation is at each end of the track, the rail potential to remote earth changes to approximately -8V near the two substations and +7V at the train location. This positive voltage is seen only for a shorter distance on either side of the train location. The negative rail potential is held at or near earth potential for most of the length but it rises to peak rail potential near the train location away from the substations which is the centre of the track. Reducing the feeding distances reduces the amount of current to be returned to any one substation resulting in the reduction of track voltage drop, thus reducing the amount of stray current from the rails.

The model does present some very minor differences in rail potential between the two scenarios with the substation at the end of the line (blue and red lines in Figure 50 above), however, that difference is insignificant. This is because the substations are not exactly located at 0km or 2km. For more accurate results, the simulation model is designed such that the track start and end locations should not overlap/match with the train and substation locations. Therefore, the load locations (train and substation) are assumed to be slightly away from begin and end points of the track.

6.6.2 Rail Resistivity

This section compares the results of the simulation model based on two different rail resistance values. For the initial case study, a rail resistance of 0.06Ω/km is considered whereas a rail resistance of 0.04Ω/km is considered for the revised case. Rail resistivity is mostly based on the type of rail used and its cross section and weight. Different size and type of rail is provided by different manufacturers. Based on the design loads, design life, cost, and other track requirements, the transit agency decides on which vendor to select. The rail type used for this analysis is V149E-1, which represents a rail resistivity of 0.04Ω/km. The remaining design parameters are the same as in section 6.6.1. Substations are considered to be at each end of the track that is at 0km and 2km for the case studies presented in this section. Table 16 illustrates the different values of the rail resistance and other design details. Figure 51 illustrates the rail potential produced for different rail resistance values.

Table 16: Rail Resistance Case Study and Design Parameters

Parameters	Case Study 1	Case Study 2
Length of Track	2km	2km
Number of Substation	2	2
Trail Location	1km	1km
Substation Resistance	0.06Ω	0.06Ω
Train Current	1000A	1000A
Rail Resistance	0.06Ω/km	0.04Ω/km
Positive feeder resistance (OCS)	0.1875Ω/km	0.1875Ω/km
Cross Bonding	1 @ centre of track	1 @ centre of track

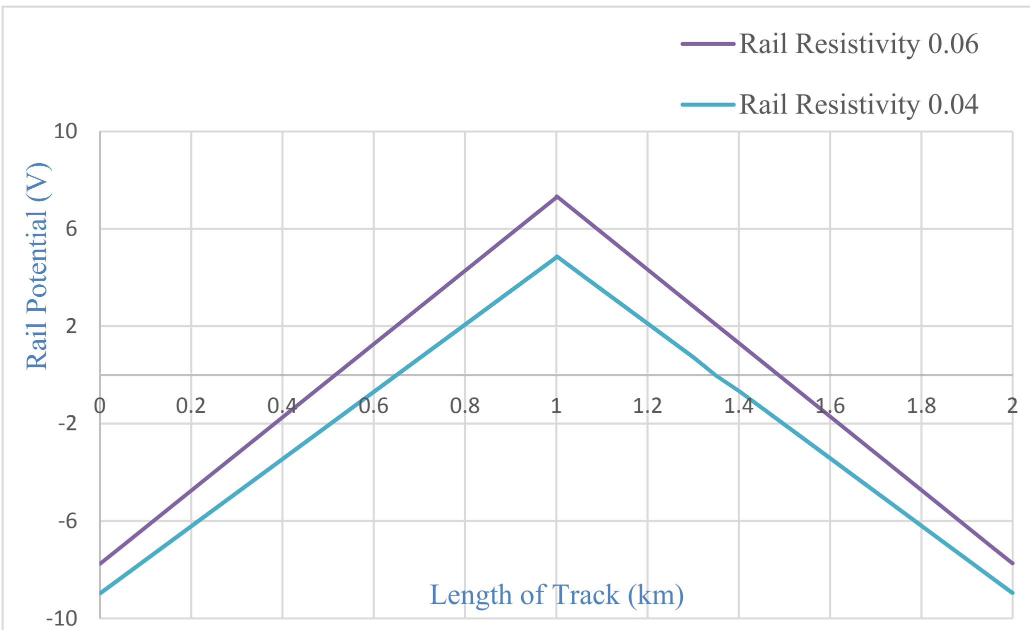


Figure 51: Effect of Rail Resistivity on Rail Potential in a Floating System

The assessment shows the benefit of reducing rail resistance, at a constant track-to-earth resistance, on stray current leakage. The original case study assumed a value of 0.06Ω/km for the rail resistivity (per rail), which shows a positive rail potential of approximately 7V at the train location (positive potential denotes current leakage to earth). The revised simulation model uses a lower value of 0.04Ω/km. As demonstrated in Figure 51, there is a noticeable impact on the output of the model, which shows a positive rail potential of approximately 4.8V. The model shows relatively less stray current leakage (positive rail potential) at the train location. The slightly higher negative potential values represent the rail return current which returns to the substation via rails.

This analysis of the simulation model validates the stray current control measures identified in Chapter 5, which recommend using low resistance rail sections for the control of stray current at the source. The literature search suggests, and the simulation model proves, that low resistivity rails can carry higher rail potential. However, actual analysis of rail resistivity is absent from existing literature, particularly when actual track parameters are used.

Using the parameters from Section 6.4, Table 17 demonstrates and compares the results of stray current leakage calculated using the BS EN 50122 for varying rail resistivity with the basic simulation model results. The results obtained using the simulation model are within 1% of the results calculated using BS EN code.

Table 17: Stray Current Leakage Calculated Values

Rail Resistivity	BS EN 50122-2	Model
Stray Current when R_R = 0.04Ω/km	50mA	50.22mA
Stray Current when R_R = 0.06Ω/km	75mA	75.31mA

6.6.3 Cross Bonding

The effect of cross bonding of the two tracks is studied here to get an idea of its impact on the rail potential and corresponding stray current leakage seen on the transit system. The cross bonds are assumed to be made of copper, 3m long with a cross section of 240mm^2 and a resistivity of 0.08Ω/km.

This section demonstrates the results of the simulation model that calculates the rail potential on two parallel tracks (track 1 and track 2) with and without cross bonding. The first case study considers a train on track 1 only and no cross bonding between the two tracks. The second case study considers a train on track 1 but this time with cross bonding between the two tracks at a distance of 1km from each substation. Rail resistance of 0.06Ω/km is considered for all the case studies. Substations are considered to be at each end of the track that is at 0km and 2km for the case studies presented in this section. Table 18 illustrates the input parameters for the model.

Table 18: Cross Bonding Design Parameters

Parameters	Details	Details
Length of Track	2km	2km
Number of Substation	2	2
Trail Location	1km	1km
Substation Resistance	0.06Ω	0.06Ω
Train Current	1000A	1000A
Rail Resistance	0.06Ω/km	0.06Ω/km
Positive feeder resistance (OCS)	0.1875Ω/km	0.1875Ω/km
Cross Bonding	None	1 @ km

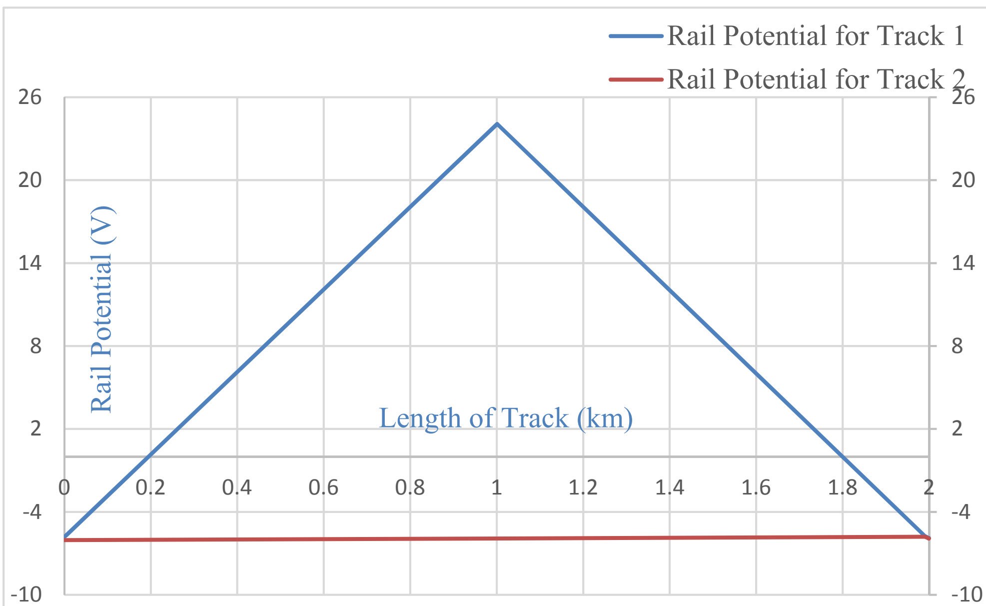


Figure 52: Effect of no Cross Bonding on Rail Potential for Floating System

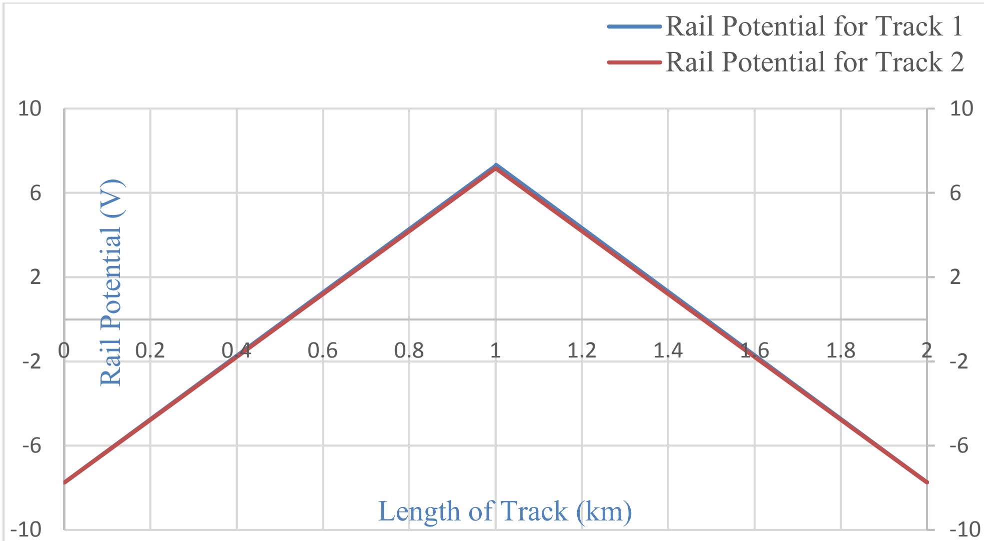


Figure 53: Effect of Cross Bonding at Centre of the Track on Rail Potential

Figure 52 illustrates the rail potential on both tracks when there is a train on track 1 only and no cross bonding. Whereas Figure 53 illustrates the rail potential on both tracks when there is a train on track 1 and cross bonding at the centre of the tracks.

The rail potential for track 1 in the first case study shows higher potential values through the length of the track with the highest positive value of approximately 24 V at the train location. In comparison to track 1, track 2 shows constant negative potentials since there is no train on this track and for that matter no leakage. This clearly emphasizes the need of cross bonding between the two tracks which will further minimize the resistance of the negative return path and thus the generation and leakage of stray current.

The second case study uses the same design parameters as the first case study except that this time there is cross bonding between the two tracks. The change in the rail potential for both the tracks is evident in Figure 53 and speaks to the fact that cross bonding provides a parallel low resistance path for the potential to the substation. Both tracks show the highest positive potential of approximately 7V at the centre of the tracks. Due to the cross bonding, both the tracks show similar rail potential throughout the track length with the exception where there is a train on track 1. At the train location track 1 shows a slightly higher positive rail potential. Another scenario that can also be analysed using the simulation model is the use of frequent cross bonding, this is presented in section 7.1.

A study by Bahra [42] reveals that it is a common practice in dc electrified rail systems to bond the rails of each track and to cross bond the parallel tracks. This analysis of the simulation model validates that the presence of cross bonding results in an effective reduction in the level of rail potential thus reducing stray current. The results also confirm the stray current control measures identified in Chapter 5 which recommend using frequent cross bonding for the control of stray current at the source.

6.6.4 Collection Mat

The need for a collection mat is initially determined based on the findings of the baseline soil data, rail-to-earth insulation levels, high traffic area, and the calculation of the transit system model operations rail-to-earth voltage profiles. Based on the findings, a collection mat may be provided if the stray current for a given transit system is high.

The cross-bonding model from the previous section is enhanced to simulate the effect of a stray current collection mat for the overall system. The modelling provides the potential profile for the stray current collection mat. This helps in assessing the amount of current leakage from the rail that enters the collection mat and its associated potential corrosion to the neighbouring infrastructure in the absence of the mat. This type of modelling constitutes a more realistic analysis that is studied to investigate the performance of actual transit systems and is absent from previous studies.

It is understood that the welded collector mat underneath the rail, in the concrete structure, is present for backup stray current protection of the nearby utilities. For this strategy to succeed, the collection mat must offer a significantly lower resistance path to the stray current, from the rail (rail potential model described in previous section with no cross bonding), than the other conductive paths (metal utilities). This includes high resistance soil which leads to increased current on the mat. Thus, the continuously bonded collector mat is modelled to provide a low resistance path. In a floating system the collection cable is not bonded to the running rail. However, a copper cable is modelled to be bonded to the stray current mat to carry the current to the rail near the substation.

The model requires a value for mat to earth resistance. Generally, this value depends upon the number, diameter and layout of reinforcement in the mat, location of the mat with respect to the rail and earth, and concrete resistivity which is variable depending upon moisture content. To further investigate the sensitivity of the model, a simulation has been run with a value of 100Ω/km and 1Ω/km for stray current output to the mat to earth resistance parameter. The results are summarized in Table 19 and are based on the same parameters as defined in Table 18 above with the exception of mat to earth resistance.

Table 19: Effect of Mat to Earth Resistance

Mat to Earth Resistance	Max. Collection Mat Potential	Total Stray Current
100Ω/km	5.606 (V)	0.1121 (A)
1Ω/km	0.089 (V)	0.1736 (A)

Table 19 shows that there is an increase in stray current discharge with the reduced mat to earth resistance. This increase in stray current discharge would have a negative impact on corrosion risk to the structures. Given that the reinforcement mat will be contained within the track plinth and directly beneath the rails in the embedded track slab, the use of the 100Ω/km is considered valid (assumed by consultants in the past and mentioned during consultant interview).

Figure 54 and Figure 55 illustrate the rail potential on the collection mat underneath track 1 (that is the track with the train) for both case studies mentioned in the cross-bonding section above (when tracks are isolated and cross bonded respectively).

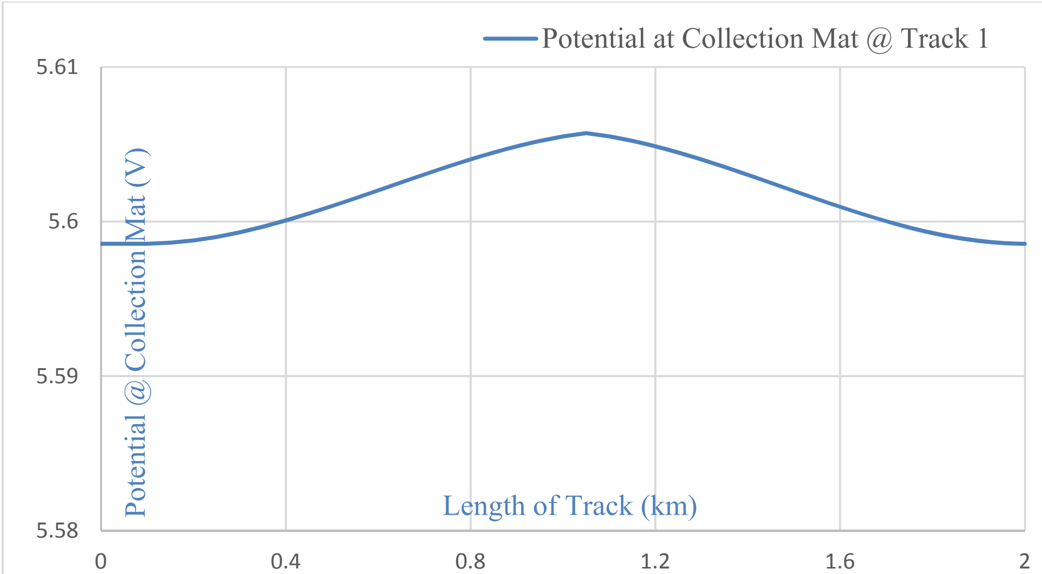


Figure 54: Potential on Collection Mat with no Cross Bonding

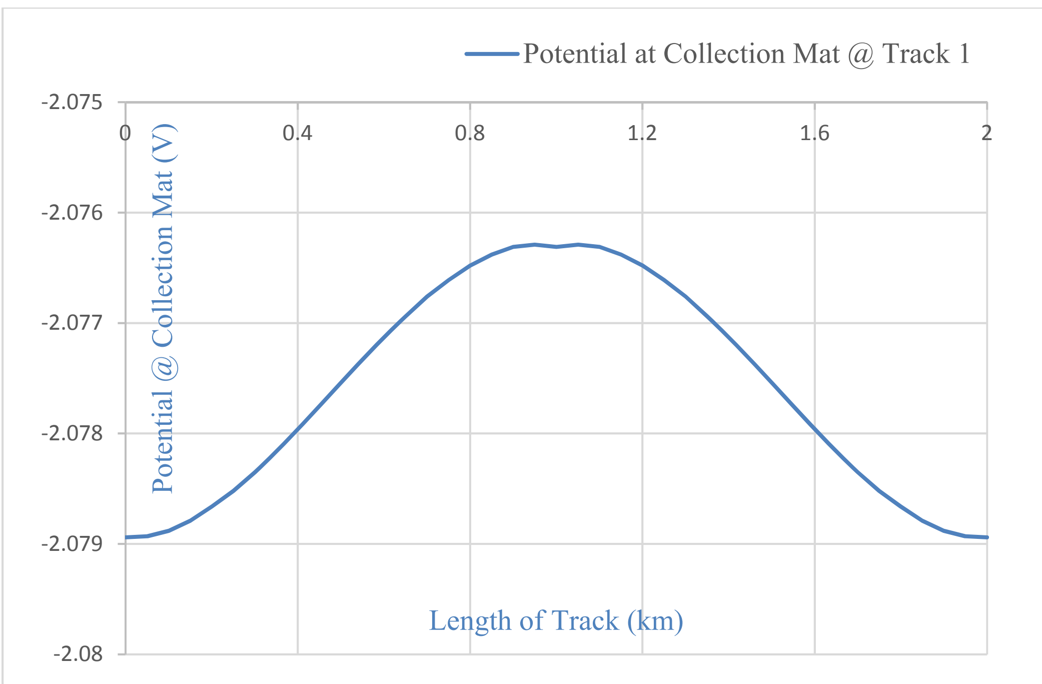


Figure 55: Potential on Collection Mat with Cross Bonding

Figure 54 illustrates the positive potential on collection mat under track 1 for the case with no cross bonding. For this scenario, as shown in the previous section, the leakage potential (positive potential) from the rail is much higher than when compared to track 1 with cross bonding. The results clearly demonstrate that the stray current collection mat provides a conductive path through which the leaked potential from the rails (from model with no cross bonding) enters the mat and the net potential leakage is reduced to approximately 5.6V that runs through the length of the mat. This positive potential leaves the mat to the earth and can flow back to the substation without causing substantial risk of corroding the utility infrastructure in the vicinity. This is particularly important in cases where total stray current for a system is high. Moreover, the analysis shows that the cross bonding of the two parallel tracks reduces the rail potential leakage to the earth. Figure 55 shows that there is no positive potential (that is no stray current) for cases where cross bonding is provided along with the collection mat. The potential profile presented above for the collection mat case is consistent with the cross-bonding scenarios. This is expected in these static models, because the trains are at the same discrete location and therefore this limits the current exchange between the two tracks when they are cross bonded.

A mat to earth resistance value which is greater than 100Ω/km would be expected to increase the amount of current contained within the mat and reduce the current discharge to earth, while the total current returning to the rails would be unaffected. Increasing the area of mat reinforcement also results in minimizing corrosion risk. The additional surface area is required to reduce the current density and hence the corrosion rate and risk of damage. This is further explained in section 7.4.

6.6.5 Rail-to-Earth Resistance

As the current return path to the adjacent substation increases, the rail potential increases as does the stray current. The track type along the track and in the immediate vicinity of substation plays an important role in keeping stray currents under control. It is a general industry understanding that the ballast section will have a high rail-to-earth resistance and thereby a reduced stray current as compared to embedded track.

Changes in stray current can be explained by the deviations in rail-to-earth resistance as the track type varies from embedded to ballast and vice versa. It was recognized during the literature review and agency surveys that at construction the values of rail-to-earth resistance are likely to be higher than during operation phase of a dc rail system. These rail-to-earth resistance values are planned and maintained in order to ensure particular insulation levels. If regular maintenance and cleaning of the track is not performed, the level of rail-to-earth resistance will fall and hence the level of stray current will increase.

Using the Fortran simulation model, a primary assessment was performed on the data produced with only one cross bond and rail-to-earth resistance values of 100Ω/km and then with 10Ω/km. It was recognized that the results from the degraded operation with rail-to-earth resistance reduced to 10Ω/km showed higher potential values and higher total stray current thus demonstrating the importance of maintaining good levels of rail insulation. It was further analysed that the stray current rises significantly as the rail-to-earth resistance continues to degrade.

Table 20: Track-to-Earth Resistance (Degraded Operation)

Substation	Distance (km)	Single Track-to-Earth Resistance (Ω/km)	Max. Rail Potential (V)	Total Stray Current (A)
LOC 1 to LOC 2	1.67	100	-10.754	**0.0**
LOC 1 to LOC 2	**1.67**	**10**	**11.205**	**0.145**

As stated in the literature search, the results from the model demonstrate that the track-to-earth resistance must be maintained at or above the systems assigned values, for the majority of the operating period. Regular maintenance and cleaning must be undertaken to minimize degradation of the track-to-earth resistance.

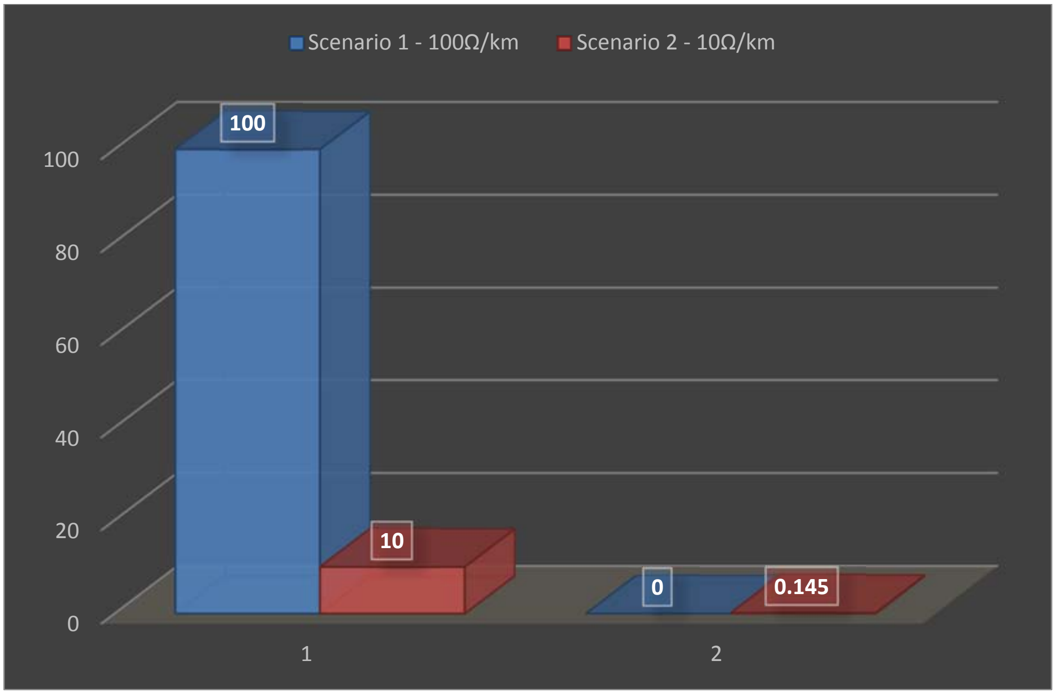


Figure 56: Total Stray Current for Degraded Track-to-Earth Resistance

Using the parameters from Section 6.4, Table 21 below demonstrates and compares the results of stray current leakage for the degradation of the track-to-earth resistance. Table 22 represents the effect of varying rail-to-earth resistance for a fixed length of the system with two different track types. The results show that the stray current leakage is higher along the section of the length with lower track-to-earth resistance. This is also suggested in the literature search and shown in Table 1 in Section 2.2 where the tracks with higher rail-to-earth resistance, mostly ballasted track, have relatively lower stray current leakage. This is because the entire rail does not require continuous isolation from earth and separation is generally needed at the contact points which are mostly insulated. As a result, ballasted tracks present less opportunity for the stray current to leak through the tracks.

Table 21: Stray Current Calculated Values (degradation of track-to-earth resistance)

Track-to-Earth Resistance	BS EN 50122-2	Model
Stray Current when resistance = 100Ω/km	50mA	50.22mA
Stray Current when resistance = 2Ω/km (minimum permitted by BS EN 50122-2)	2.5A	2.58A

Table 22: Stray Current Calculated Values (varying rail-to-earth resistance)

Track-to-Earth Resistance	Model Results
Stray Current when resistance = 100Ω/km for entire section	50.22mA
Stray Current when resistance = 100Ω/km from 0-0.49km and 10Ωkm from 0.5-1km	0.52A (.10A for 0-0.49km & 0.42A for 0.5-1km)

6.7 Metal Loss Calculation

An account and evaluation of the previously developed simulation models along with their capabilities and limitations is presented in the literature survey of this thesis (chapter 2). The majority of the simulation models presented [27] can only describe the stray current level exiting the rail of the various dc traction design schemes. They do not provide any information concerning the corrosion risk and subsequent metal loss to any third party infrastructure in the vicinity of the transit system. This section presents the basic methodology for the calculation of the corrosion risks.

The modelling approach taken here follows the basic principle of Faraday's law which states that "the amount of metal dissolved in a corrosive reaction is proportional to the electrical charge that causes the reaction". To begin with it is first concluded that the corrosion is electrochemical and is caused by stray current interference. Therefore, using basic equations 28 thru 31 for volume and mass loss, and assuming the following parameters for a presumed utility pipe the allowable current density (SC_d) is calculated as 1294.4μA/m^2 for the pipe over its design life of 100 years.

- mass of metal loss (Iron) per Ampere = 9126grams (from section 2.1.1),
- assumed utility/pipe diameter (d) = 25mm,
- length of pipe considered (l) = 1000mm,
- assumed allowable metal loss (cracking) (c) = 0.15mm,
- density of steel (D)= 7.9g/cm^3, and
- assuming percent of surface area exposed (S_a)= 50%,

$$V_l = \left(\frac{\pi}{4}d^2 - \left(d - 2(c)\right)^2 \frac{\pi}{4}\right).l.\frac{Sa}{100} \tag{28}$$

$$M_l = V_l.D\frac{1}{1000} \tag{29}$$

$$C_c = M_l . \frac{1}{(mass\ of\ Metal\ Loss\ in\ grams)(Design\ Life)} \tag{30}$$

$$SC_d = C_c \,/\, \left(\frac{\pi}{2} d.l\right) 10^{12} \tag{31}$$

Where V_l = *Volume loss*

M_l = *Mass loss*

Cc = Continuous Current

This allowable current density is further used to calculate the continuous current in the utility, corrosion current density, and allowable stray current for the utility based on the worst case scenario. A more detailed assessment has been made of the impact of stray current on a coated pipe in the next chapter.

6.8 Summary

The simulation model formulated in Fortran, by the author, results from the nodal analysis of resistive networks. This model significantly enhances the accuracy of the results, helps in the analysis and effectiveness of closely spaced substations, cross bonding, and the stray current collection mat. The model is useful in terms of its ability to perform a preliminary corrosion risk assessment of a DC traction system, (i.e. rail leakage current and the impact on a third-party utility pipe). The ability of the model to provide the analysis of the following transit system parameters and to validate their impact on the rail potential and total stray current is an asset:

- Rail resistivity
- Cross bonding the two tracks
- Collection mat potential
- Rail-to-earth resistance degrading option
- Metal loss potential analysis and simulation

The literature review discusses these elements [27, 74] but the actual analysis of these parameters and their true effect on stray current leakage in a real transit system was absent from previously developed simulation models of such kind.

Though the analysis is carried out for a floating system, as it is considered the optimum option, the model can be modified to a diode bonded system. Whilst the static models, where the train is at a fixed point in time, can be applied to demonstrate the principles of the problem discussed, dynamic models can be utilized to obtain a comprehensive account of the effect (this is carried out in the next chapter).

Based on the analysis carried out in this chapter, it would be safe to conclude that the placement of the substation locations with respect to the train will have an effect on the rail potential and thereby the stray current level produced. It can be concluded that the presence of cross bonds results in an effective reduction of the level of potential and thus corrosive charge. It was also analysed that smaller changes in stray current can be observed and explained by the change in rail-to-earth resistance as the track type changes from embedded to ballast and vice versa and when the rail-to-earth resistance changes with time due to lack of maintenance.

7 Stray Current on dc Transit System

Researchers are cognizant that many of the present simulation models are limited to simple geometries and are based on numerous exemplificative assumptions that can potentially lead to inaccuracies. The model presented in the previous section replicates real life transit system scenario for a simple two substation condition by using actual design parameters. In that it overcomes the limitations of existing simulation models from a real life transit system.

The main objective of this chapter is to enhance the stray current modelling presented in the previous chapter by using the input parameters from the traction power design of an existing light rail transit system. Most static models are applied to demonstrate the principles and validate various assertions. This stray current model is based on a dynamic assessment rather than single values of current or voltage. The location of the trains and their respective loads (currents) are taken from the traction power study.

The stray current model can be used for any number of substation locations along any transit system. However, for the purpose of understanding the modelling process, two substation locations (at each end of the track) are considered in the model below. Stray current is then calculated based on service during normal operation, instead of an assessment on short duration fault conditions. This model establishes a more realistic case study that can be utilized to investigate the performance of a dc transit system, the impact of stray current on third party infrastructure (metal loss) and the design of a stray current collection mat.

7.1 Model

The model developed and presented here is used to simulate two parallel tracks with a train on each track. The current flow both on and off the rails and to and from earth at each node can be calculated by the stray current model for each varying interval. The collection mat in the reinforced concrete track bed is intended to capture a portion of the stray current from the running rails. This reduces the risk of corrosion to the utility pipes and assists in predicting the stray current discharge for corrosion calculations. Figure 57 shows a typical traction power supply and return circuit system for dual track with cross bonding and collection mat.

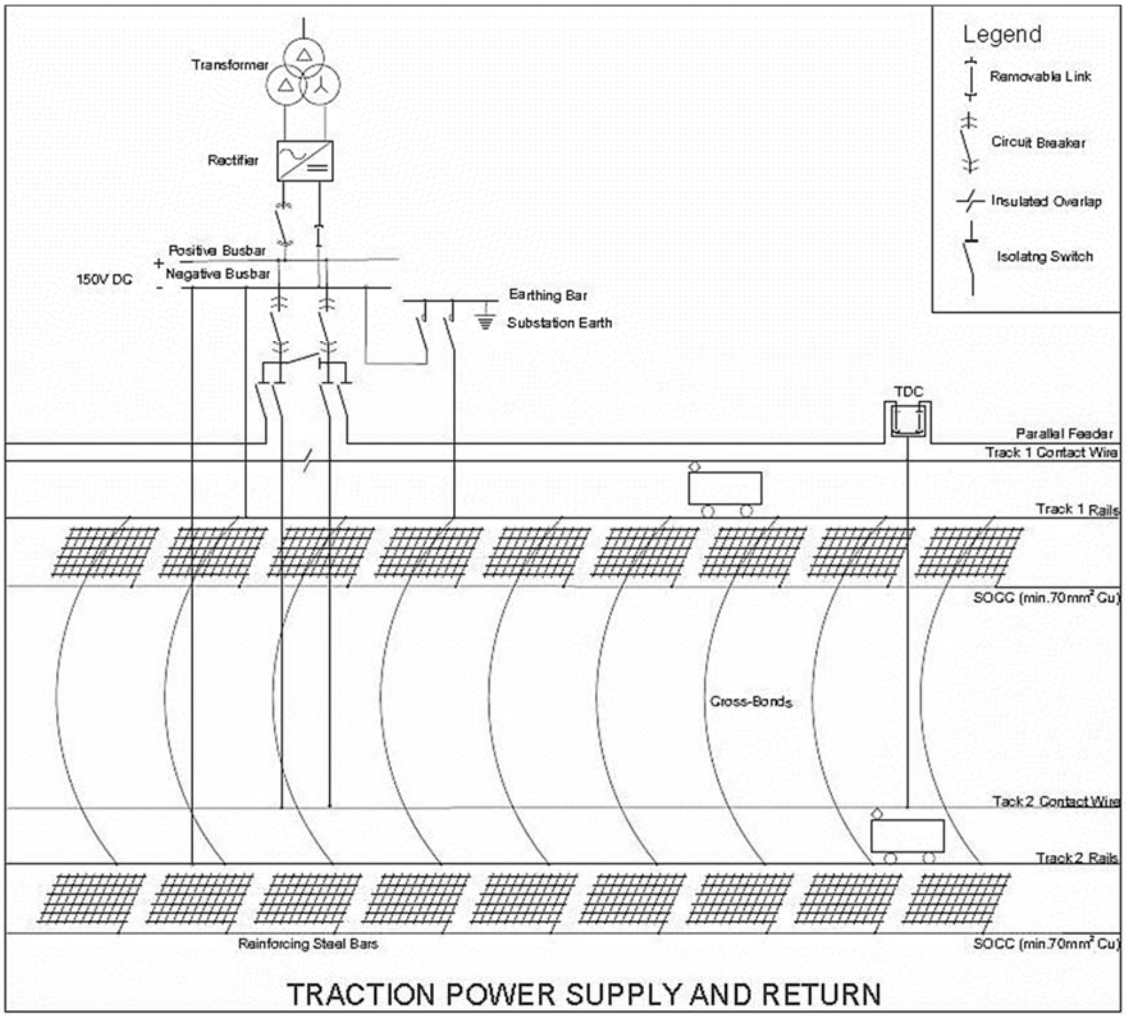


Figure 57: Typical Parallel Track Traction Power Supply and Return Circuit

The system model is completely dependent on the traction power data and the actual design parameters for a light rail transit system as provided by the transit system and as detailed below;

<u>Traction Power Substation Data</u>

All substations are modelled by a Thevanin equivalent voltage source (constant voltage in series with a resistance) in the traction power simulator and is a given parameter for this model. The constant voltage is set to the substation rectifier no-load voltage 791V in accordance with the power systems design. The traction power system is designed to operate at a nominal voltage of 750V and a full load current as defined in Table 23 below.

From these values the equivalent internal resistance (R) of the substation is calculated as:

$$R = \frac{791(\mathrm{V}) - 750(V)}{Full\ Load\ Current\ (A)}$$

Table 23: Substation Location and Resistance

Substation (Abbreviation)	Capacity (kW)	Location (km)	Spacing (km)	Current I – (A)	Resistance R – (Ω)
Location 1 (LOC 1)	900	0.000	1.670	1200	0.034
Location 2 (LOC 2)	1500	1.670	1.670	2000	0.0205

DC Positive and Negative Feeder Resistance

A 240mm^2 copper cable with a resistance of 0.08Ω/km is used for the 4 positive feeders. Each positive feeder is 20m in length

A 400mm^2 cable with a resistance of 0.05Ω/km is specified for the 5 negative feeders for each track. Each negative feeder is 50m in length.

Table 24: Positive and Negative Feeder Resistance

Substation	Positive (Supply)			Negative (Return)		
	Cable Resistivity (Ω/km)	No. of Cables	Total Resistance (Ω)	Cable Resistivity (Ω/km)	No. of Cables	Total Resistance (Ω)
LOC 1	0.08	4	0.0016	0.05	5	0.0005
LOC 2	0.08	4	0.0016	0.05	5	0.0005

Track Distribution Cabinets (TDC's) & Paralleling Points (PP's)

TDC's are located throughout the actual line connecting the parallel feeding cables to the catenary. The locations of the TDCs and PP are based on the Overhead Contact System (OCS) design details. Though the model is designed to take in to account the TDCs and/or PP's locations, however, they are not considered between the two substations for this analysis.

Overhead Contact System & Running Rails

The overhead contact wire is a single 120mm^2 conductor with a resistivity of 0.1875Ω/km.

A value of 0.04Ω/km is used for the rail resistivity (per rail); this is the maximum value given in the actual project requirements.

Track-to-Earth Resistance

As stated in previous sections, the track-to-earth resistance determines the amount of stray current that leaks into the ground and the rail touch potential. The number of track types is simplified to two for the actual line; an embedded track with a resistivity of 10Ω/km, and ballast track with a resistivity of 100Ω/km is used in accordance with the project requirements. However, only one track type, that is embedded track, is taken for the section between the first two substation locations.

Table 25: Track-to-Earth Resistance

Substation	Distance (km)	Track Type	Single Track-to-Earth Resistance (Ω/km)
LOC 1 to LOC 2	**1.67**	**Embedded**	**10**

Cross bonds

Track cross bonds are modeled every 300m between the up and down track rails (this spacing is in line with the findings of the literature search). The cross bond cable is a 240mm^2 copper cable of resistivity 0.08Ω/km. The cross bond is assumed to be 3m long. The locations of the cross bonds are detailed in the Table 26 below.

Table 26: Cross bond Location and Resistance

Number	Location (km)	Resistance (Ω)
1	0.0	**0.00024**
2	0.3	**0.00024**
3	0.6	**0.00024**
4	0.9	**0.00024**
5	1.2	**0.00024**
6	**1.5**	**0.00024**

Stray Current Collector System

The stray current collector mat is modelled with conductivity equal to 0.25Ω/km in accordance with the actual project requirements. The stray current collector cable is a $70mm^2$ copper cable which is modelled as a conductor bonded every 300m to the stray current mat. Mesh to earth resistance of 100Ω/km is used when accounting for the collection mat.

The input data that was provided was, repeated, every four minutes corresponding to the train headway. Therefore, it is assumed that every four minutes a train is exactly at the same location. Table 27 shows the remaining input parameters for the model.

Table 27: Substation Design Parameters

Parameters	Details
Length of Track	1.67km
Number of Substation	2
Train Location (train 1 @ track 1)	1.043km
Train Location (train 2 @ track 2)	0.801km
Train Current (train 1)	53A
Train Current (train 2)	223A
Positive feeder resistance (OCS)	0.1875Ω/km

To assess the impact of current returning to the rails it is assumed that all the current going in to the stray current mat will discharge off the mat located directly under the rails. A proportion of the current returning to the rails will have come along the mat and collector cable, with the remainder from the earth in the vicinity. The results of the model demonstrate a total stray current of 0.0046A along the track length which translates to 2.73µA/m (0.00273mA/m). This value is significantly lower than the suggested value of 2.5mA/m in the BSI code and, as stated in the section 6.5, not enough to carry out a detailed analysis. Figure 58 illustrates the rail potential along the track for the model whereas Figure 59 shows the maximum stray current leakage from the mat.

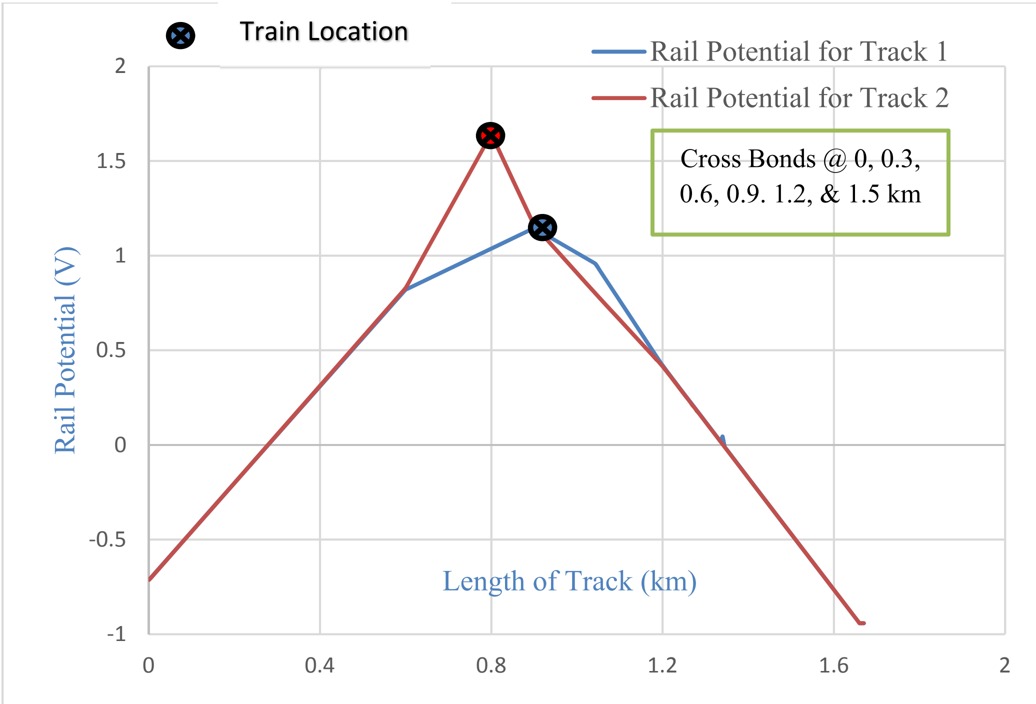


Figure 58: Rail Potential for Two Track Transit System with Cross Bonding

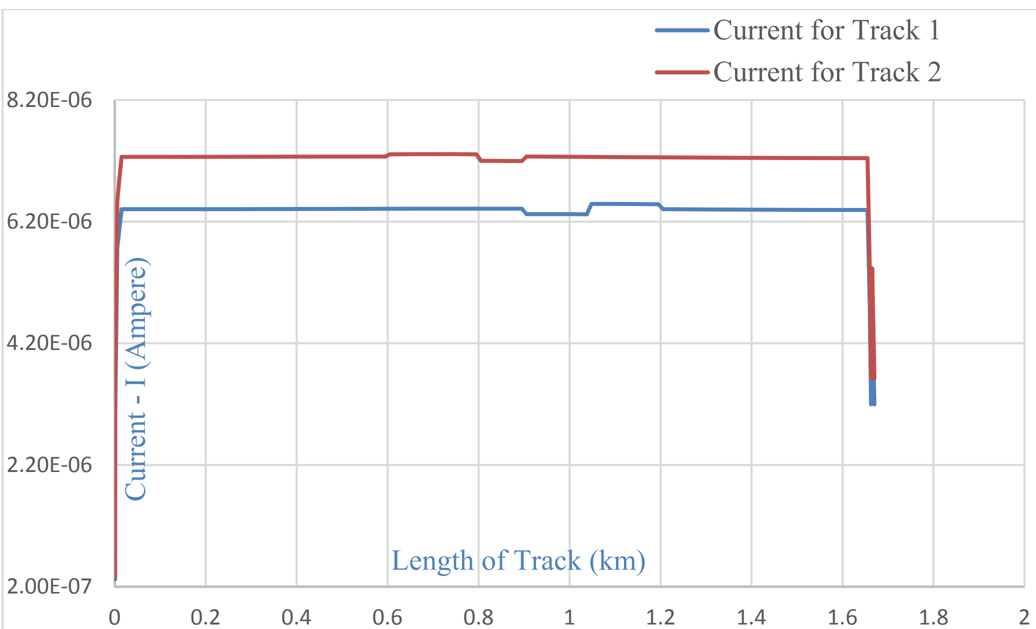


Figure 59: Maximum Stray Current for Two Track System

The results are broadly in line with expectations. The substation at the beginning of the track is of a smaller capacity (900kW) than the other substation (1500kW). This results in more power being supplied from the substation at the end of the tracks (power is supplied from the substations at each end). Overall, there is more current leaking from the centre of the route than at the extremities since substations are at the end of the line and as explained for a floating system. The mat under the rail, as designed, collects this positive voltage and transfers it to the nearest substation by providing a low resistance path. However, based on the mat to earth resistance, the mat can only carry a certain potential and the excess results in stray current discharge to the earth as presented in the Figure 59. This stray current causes damage to the metallic utilities and/or other infrastructure nearby. However, since the return current path is shorter, the rail potential is less and thus there is a reduced level of stray current overall.

For a transit system at grade the main corrosion risk is to the rails and its components as well as to any metallic infrastructure in the vicinity. The level of corrosion may influence the design life of the rail and other metallic infrastructure and thus this should be considered at the start of the system design. This risk can be reduced by effective design of the of track-to-earth resistance, rail return resistance, traction power substation spacing, conductance of negative conductors, modification of surrounding underground utilities, cross bonds, and magnitude of propulsion current.

7.2 Comparative Analysis of the Simulation Model

Most new transit systems have realized the effect and importance of closely spaced substations, cross bonding, and rail-to-earth resistance in the control and mitigation of stray current. However, some of the transit owners and designers are still uncertain on lowering the rail resistivity and on the use of stray current collection mats. Therefore, to provide comparative analysis and to evaluate the effect on a real life transit system, the simulation model described in section 7.1 was modified by changing the rail resistivity to 0.06Ω/km and by assuming that there is no stray current collection mat.

Figure 60 illustrates the rail potential along the track for the revised model when the rail resistivity is 0.06Ω/km. Comparing the results with Figure 58, it is evident that though slightly, but the rail potential does increase. This increase in positive rail potential will increase the stray current leakage giving a total stray current of 0.0051A along the track length which translates to 3.10μA/m (0.00310mA/m). This total stray current is 1.14 times higher than the one calculated in section 7.1 using rail resistivity of 0.04 Ω/km.

This analysis of the simulation model validates the conclusion made in section 6.6.2 that recommends using low resistance rail sections for the control of stray current at the source.

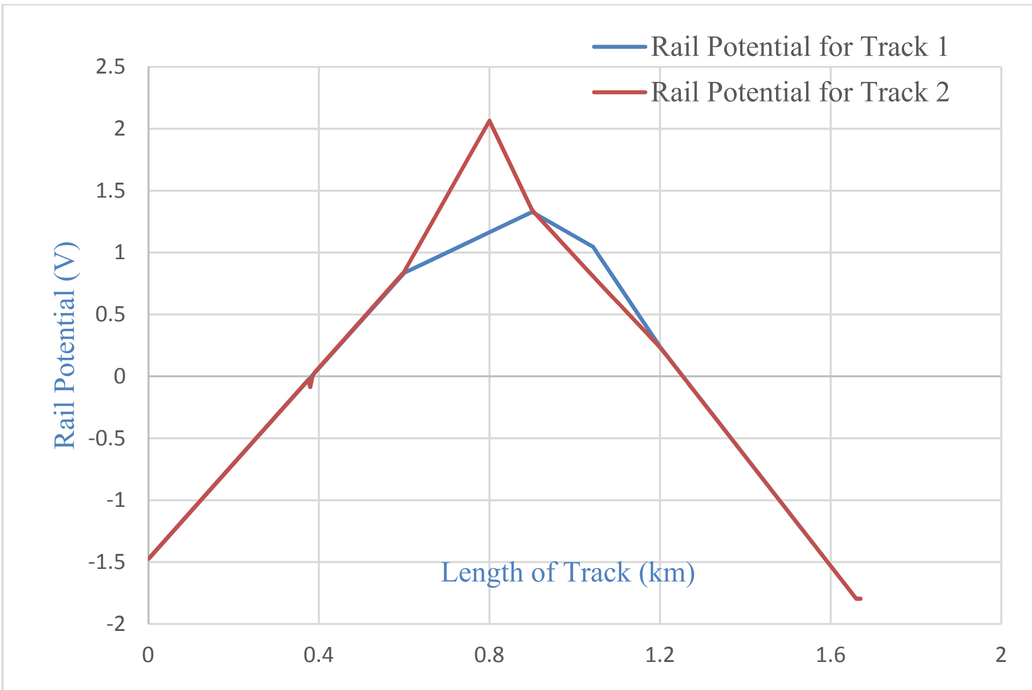


Figure 60: Rail Potential for the Transit System with Rail Resistivity 0.06Ω/km

7.3 Dynamic Modelling

The effect on the amount of stray current due to different train locations and their respective load (current) values can be comprehensively described and analysed using the dynamic modelling. In this section a simple dynamic model has been presented in which the train has been moved along the length of the track while drawing a constant load (current). Except for the constant load value of 500A for both the trains and the varying location of the two trains along the track the rest of the parameters are the same as defined in section 7.1 above.

The trains, as shown in Figure 61, are assumed to be on parallel tracks approaching from opposite direction to each other and are traveling towards the substation away from each other. Starting from the substation and ending at a substation, five different train locations are presumed for each train. The model performs the analysis for each set of locations, draws the result, and then starts the loop to run the second set of locations. This cycle continues for the predefined five iterations. The total stray current at these locations for the system is calculated and defined in Table 28 below. This simulation approach can be carried out for more than five iterations, which will not only aid in identifying the worst case scenario based on the location of the trains but will also help the designer in taking the appropriate stray current control measures.

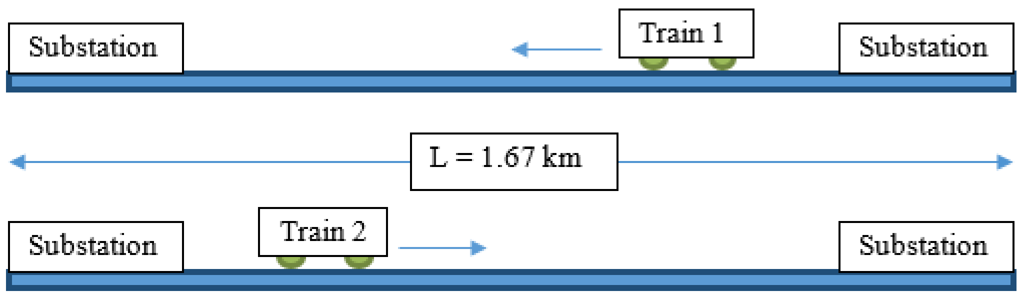


Figure 61: Train Location

Table 28: Maximum Stray Current

Scenarios	Train 1 Location	Train 2 Location	Total Stray Current
Scenario 1	0	L	0.032A
Scenario 2	¼ L	¾ L	0.081A
Scenario 3	½ L	½ L	0.046A
Scenario 4	¾ L	¼ L	0.058A
Scenario 5	L	0	0.024A

As mentioned in earlier sections, for an actual transit system the traction power model will simulate timetable operations and will provide the output for the rail-to-earth voltage and current drawn. The train locations for different scenarios with high load requirements and with positive rail potentials can then be provided and used in the above simulation model to calculate the leakage current (the example was presented in section 7.1). Figure 62 shows the total stray current with reference to the varying train locations.

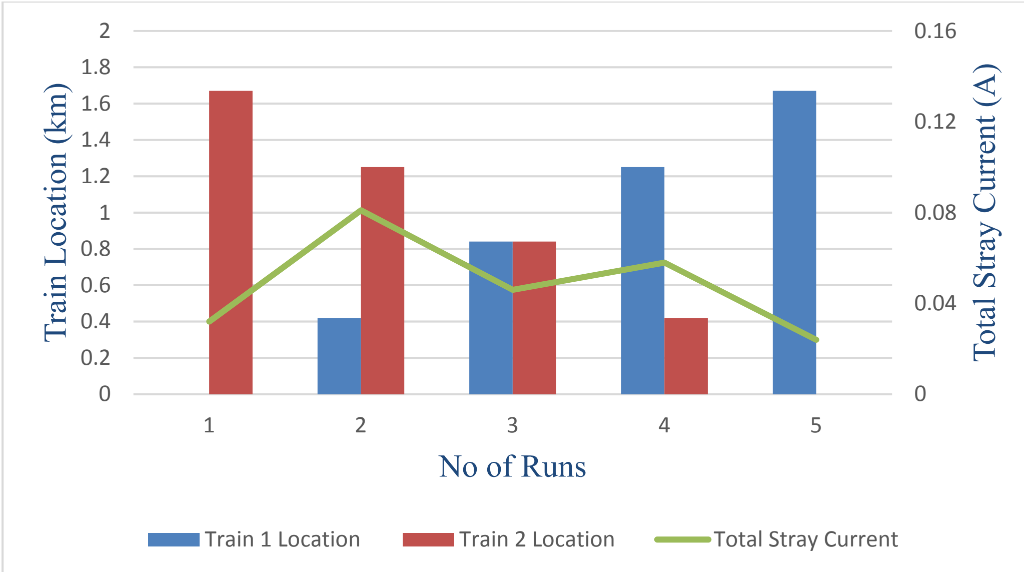


Figure 62: Total Stray Current with Respect to Varying Train Locations

As explained earlier, the substation at the beginning of the route is smaller in capacity than the substation at the end of the route. Consequently, more power is predominantly supplied from the higher capacity substation. As the current return path is larger to the adjacent substation, the rail potential increases and similarly does the stray current.

7.4 Corrosion Assessment of Utility

For corrosion modelling and assessment purposes it is the continuous or total stray current that is required to estimate the long term cumulative damage. This value has been calculated in section 7.1 using the stray current model. The traction power sample used above is representative of the morning rush hour timetable and does not include current from the yard. For a more practical analysis the stray current from the yard has been assumed to be 50% of that in the line. This combined current is taken as a day time value that operates for 80% of the day (considering no train operation in the night time). Thus, the total stray current used is 0.00552A (5.52mA).

The percentage of yard current and operation time will vary for difference transit systems and thus both are input parameters which can be changed for different modelling scenarios. The model further assumes that the pipe is electrically continuous (this is not always the case, e.g. ductile and cast iron water pipes may be isolated at pipe joints) and thus provides a favourable stray current path at the joints. This situation can be modelled by breaking the track length in to different sections, if pipe joint information is available. The site of greatest corrosion is most likely to be in the vicinity of a substation where stray current will tend to return to the tracks and then to the substation.

Using the input parameters below and equations provided in section 6.7 above, in the Fortran model, a metal loss of 4.7kg per year and a metal volume loss of 636cm^3 is calculated if all of the stray current (0.00552A) were to be returning via a metal utility pipe

- mass of metal loss (Iron) per Ampere = 9126grams (from section 2.1.1),
- assumed utility/pipe diameter (*d*) = 25mm,
- length of pipe considered (*l)* = 1670m (entire length of track), and
- density of steel (*D*)= 7.9g/cm^3

If this corrosion were distributed over a large area (e.g. a large diameter pipe) the effect may only be marginal. Moreover, over a 10 m^2 area a metal loss of 636 cm^3 represents a uniform reduction in wall thickness of 0.0636mm/year. However, over smaller areas the corrosion rate increases. For 1m^2 the rate of attack of 0.636mm/year is likely higher than the typical long term uniform corrosion rate in aggressive soils. The corrosion is unlikely to be uniform and therefore localized rates of attack are possible which are highly dangerous.

The stray current model offers a detailed output which is then used to provide a comprehensive corrosion assessment of the utilities along the length of the route. Moreover, the output files from the stray current model provide potential values which can then be used to calculate the localized stray current along the length of the track. This stray current can be used to assess the localized damage to the utility line in the vicinity to avoid the danger of corrosion described above.

If the total stray current leakage is high and/or the localized attacks need to be mitigated, then an increased area of reinforcement in the collection mat can used.

7.5 Corrosion Assessment of Reinforcement Mat

The risk of corrosion to the reinforcement collection mat is also susceptible to high return currents to the rails and/or substation. To mitigate the corrosion risk on the mat one potential mitigation method is to increase the cross sectional area of the reinforcement in the mat with additional bars or increased diameters. The additional surface area is required to reduce the current density and hence corrosion rate and risk of damage.

Changes to bar diameter are only proposed for the longitudinal bars since they are the dominant bars in the mat in terms of current flow. Both the number and size of the longitudinal bars can be increased, within practical limitations, to increase the surface area to the value required and thereby reducing the percentage of allowable current. A small amount of corrosion can cause spalling and therefore loss of strength is not normally an issue [102]. Typically, corrosion of reinforcement is likely to manifest similar to concrete surfaces showing rust staining, cracking and then concrete spalling. This process is typically identified by visual inspection.

For the simulation model it is presumed that if the calculated current density for a given arrangement of bars is less than 1294μA/m² (see section 6.7) then the bar arrangement is acceptable. If the current density for a given arrangement of bars is greater than 1294μA/m², then there remains a risk of corrosion, in damaging amounts, within a 100 year design life. Additional mitigation will be required for those systems.

The simulations carried out in section 6.6.4 also represents the stray current collection cable efficiency to the collection mat area. It is assumed that a 70mm^2 collector cable results in an approximately equal current flow in both the mat and the collector cable. It is observed that as the cross-sectional area of the stray current collector cable is increased, the percentage of the total stray current flowing through the collector cable also increases.

The rail voltage profile due to the injection of current into the model track is shown in Figure 63 for the input variables defined in section 7.1. The results of the model demonstrate a total stray current of 4.6mA along the track length. This 4.6mA, 2.3mA from each of the rail will flow into the stray current collection system. It will then remain in the collection system or will flow into the soil surrounding the concrete slab.

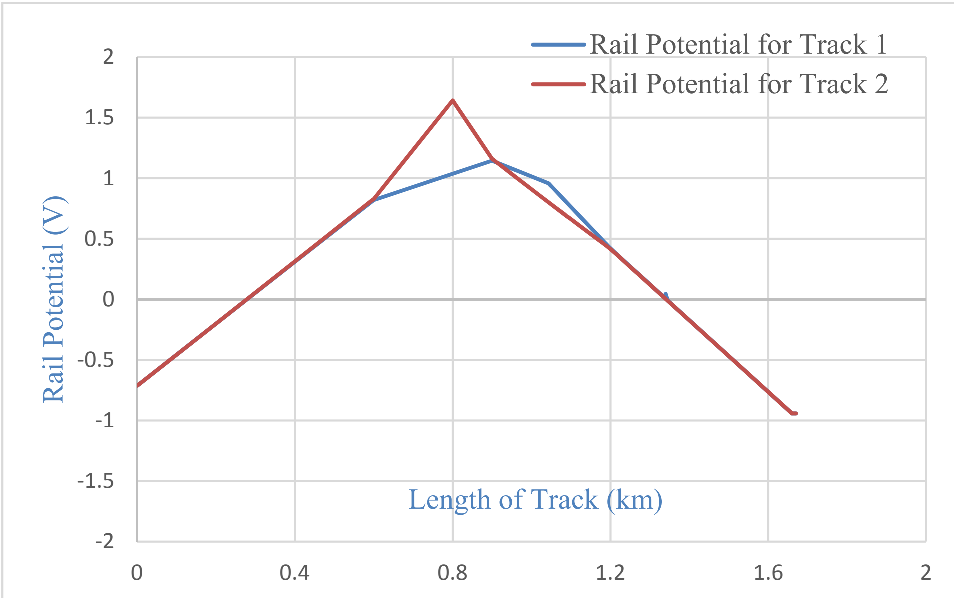


Figure 63: Rail Potential for Two Track Transit System

The approach and input parameters used in the corrosion assessment simulation model to predict the current return for a given reinforcement is as follows:

Longitudinal Bars;

- Since the longitudinal bars are continuously welded, assume the individual bar length to be equal to the length of the track (1.67km)
- Assign diameter of bars
- Assign number of bars per section
- Assume the slab to have top and bottom longitudinal layers and that the current return is limited to the top bars only (50%)

Assuming a bar diameter of 25mm, total four bars for each track (that is total of eight bars for the parallel tracks) and using the limiting current = 5.52mA (from section 7.3) the model calculates the total area of the bars to be 636m², that is the total area of discharge.

Since the majority of stray current return will occur on the longitudinal bars it is therefore prudent to only modify the surface area of these bars and leave the transverse bar diameter constant. However, using the parameters above, the current density is calculated as 84.2μA/m² which is significantly lower than 1294μA/m² and therefore the bar arrangement is acceptable.

The impact on the reinforcement mat is considered to be minimal and therefore the risk of stray current corrosion affecting the integrity of the structure is low. However, for the scenario when the current density is higher than the limiting value, the simulation model will ask for a secondary check with revised bar diameter and number of bars. To reiterate, the control of stray current leakage using collection mats can be difficult in areas where there is low soil resistivity or other highly conductive infrastructure.

7.6 Summary

The objective of this chapter was to extend the modelling technique presented in the earlier chapter.

Corrosion will occur at each point that the current transfers from a metallic conductor, such as a structural reinforcement, to the electrolyte (i.e. the soil or concrete). Hence stray current leakage can cause corrosion damage to the rails, railway metallic structures, utility pipelines in the soil and any other low resistance metal buried in the vicinity. The hazard posed by stray current is not confined to structures that are within the vicinity of the railway. Stray currents can flow considerable distances (particularly in soils of low resistivity) and can therefore cause corrosion damage to what may be considered remote structures.

The mathematical model developed in Fortran, by the author, presents a geometrically accurate model of an actual dc rail transit system. This model, based on the evaluation of resistive networks, calculates the maximum rail potential and the total stray current generated by the system based on its actual geometry. The results obtained by running it on an actual transit system data are comparable to that of the basic modelling conventions presented in the previous chapter.

The corrosion assessment programmed in this model, though pretty rudimentary, provided methodology which has not been carried out in the stray current modelling prior to this work. The assessment is performed both in terms of the evaluation of stray current that may be picked up by a utility pipe and in the assumptions regarding the condition of the utility. While it is possible that corrosion of the order given in the assessment may occur, it is also possible that the risk will be much lower. In this respect the assessment may be best used to indicate an uncertainty and be used to decide on the preferred approach to dealing with this risk. These approaches are:

- To assume that the risk of corrosion to utility structures is high. Thus, mitigate the risk as calculated above, as part of the design methods.
- To better understand the risk through testing and monitoring at specific locations. This would require establishing the base line condition on the utility with respect to stray currents prior to construction of the railway. This would then need to be followed by post completion monitoring of the works to establish any changes, attributable to the railway, as a result of its construction and operation.

It follows from the second option that if a significant risk of corrosion to utilities is attributable to the railway operation then mitigation may be required.

Higher conductivity of the stray current collection mat is achieved by electrical bonding of the reinforcement bars in parallel and by the conductivity of the copper connector cable. It can be shown, using simplified simulation, that there is an advantage in using collection mats in high resistivity soils with high stray current leakage.

8 Conclusions

8.1 Overview of Thesis

The aim of this chapter is to review the work done in the preparation of this thesis and present the main conclusions. The last part of this chapter presents some suggestions for potential future work.

The research in this thesis can be described in the following four main categories:

8.1.1 Literature Review including Existing Modelling Techniques

Chapter 2 presents a literature review of existing work. It 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 compilation of literature is distinct in that it, in an unprecedented fashion, reviews and complies the data, research, and criteria from a wide range of sources on stray current under one cover. The study and investigation encompasses the review of theoretical, practical as well as experimental approaches to address the stray current leakage and stray current corrosion issue in dc powered transit system. Although many transit agencies have their own standard criteria, it is typically not known as to how the initial limiting voltage and current values were introduced in the criteria. This is especially true when the rail transit industry in the US has not standardized any acceptable limits of negative return resistance.

Besides investigating the historical development of the stray current corrosion mitigation techniques, the literature review portion of this thesis includes the study of existing stray current modelling techniques and their restrictions to the simulation of non-dynamic conditions within a transit system. Design criteria manuals for various agencies around the world have been studied as part of the literature review to help perform a comparative analysis of different norms adopted by transit agencies.

8.1.2 Transit Agency Data Assembly, Studies, and Field Testing

Chapter 3 compiles data that was assembled by sending a questionnaire to the transit agencies inquiring about their process of stray current control and/or collection system for their real world dc powered rail transit system. Based on the findings of the questionnaire, a more detailed questionnaire was sent to select few agencies followed by a series of one-on-one interviews. The chapter also includes the findings of different stray current control criteria and testing methods adopted by a diverse cross section of national and international dc powered transit agencies.

Reviewing and compiling the result of these questionnaires and interviews highlights that in most instances the use of the limiting values for the stray current control (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 a pre-revenue testing and most of them do not have a regular testing and maintenance plan. This renders it difficult to standardize a uniform approach for dc transit system providers. The data also indicated that transit agencies are not keeping a log of the corrosion issues caused by the stray current or 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. However, 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.

A sample of the results of the questionnaire given to various transit agencies and the in person interviews is presented in Chapter 3 in a matrix format. Lastly, stray current corrosion issues for three US based transit agencies are also illustrated in this chapter.

Chapter 4 elaborates on various stray current testing procedures and their results for real life transit agency and for an actual start-up transit system. These test results are then used to compare transit agencies conformance with those respective agencies stray corrosion criteria.

This compilation of a wide range of real world data gives a unique and unprecedented one stop holistic perspective that the track-to-earth resistance for the embedded track (which is the focused track type for this thesis) largely depends on the isolation methods and technique at the time of design, construction, and then onward on the maintenance of the tracks. It also helps conclude that the 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, the type of structure under investigation and the source of leakage. This chapter strengthens the argument of performing base line survey and pre-revenue testing for a start-up line by documenting the problems identified during testing.

8.1.3 Recommendations and Guidelines

Chapter 5 uses the data collected from the literature review, stray current testing observations, coupled with the questionnaire from national and international transit agencies including interview of corrosion consultants and develops a stepwise process for achieving a uniform stray current isolation and QC for an embedded track.

This chapter highlights that the extension of an existing system can result in the increase of stray current leakage except when the older track is electrically isolated from the new track or is designed for similar or as stringent stray current control as the new track. Therefore, 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 thesis so far provides contribution to the knowledge related to stray current methodology by developing a guidebook for TRB. This guidebook will address the design of stray current control methods, sustainability of stray current control and the control of rail-to-earth voltages for dc-powered rail transit systems for North American transit agencies. The guidebook will be used by transit agencies, design and maintenance practitioners, and will influence new system construction, extensions, and maintenance and operation of existing systems. This guide book, the development of which is being spearheaded by the Author as a direct outcome of this thesis work, will be a first of its kind. The author will be preparing the guidebook for the National Academies of Science (NAS) in conjunction with TRB.

This guidebook will include, for the first time under one cover, design and sustainability of stray current control for DC-powered rail transit systems, with a primer that explains all significant issues in readily understandable terms for non-technical people, guidelines addressed to design and maintenance practitioners (e.g., recommended hazard analysis and safety certification checklist items) and case studies (third rail and overhead contact).

This is the first compilation of a guidebook in the US for stray current that identifies the domestic and international body of knowledge that pertains to principles, procedures, methods, and criteria for achieving and documenting acceptable levels of stray current and rail-to-earth potential. The guidebook includes existing and proposed standards, methods of stray current measurement, testing, and maintenance of track for of dc powered transit operators.

8.1.4 Modelling Techniques

Chapter 6 demonstrates the contribution to knowledge that this thesis offers in terms of conceptualization of the research data by developing a simulation model that performs a preliminary corrosion risk assessment of a dc traction system. The chapter presents the modelling techniques using various simulations to demonstrate the role and significance of various isolation and mitigation practices to control stray current leakage in a dc transit system. It analyses a wide range of transit system parameters like cross bonding, rail-to-earth resistance, rail resistivity, collection mat, and substation spacing, etc. to validate their impact on theoretical and best industry practices for rail potential.

The analysis carried out in this chapter helps to conclude that the placement of the substation locations with respect to the train will have an effect on the rail potential and thereby the stray current, validating the literature research (most specifically section 6.2). It can be concluded that the presence of cross bonds results in an effective reduction of the level of potential and thus the corrosive charge. It was also observed that smaller changes in stray current can be observed and explained by the change in rail-to-earth resistance as the track type changes from embedded to ballast and vice versa and when the rail-to-earth resistance changes with time due to lack of maintenance. This was validated by comparing the results of the model with best industry practices and BS EN standards for track-to-earth potential for different track types.

The results of the basic modelling presented in Chapter 6 are further evaluated in Chapter 7 on a real life transit system resistive networks, and by calculating the maximum rail potential and the total stray current generated by the system based on its actual geometry, using the stray current model and comparing the results with the allowable limits specified in the BS EN Standards. Most simulation models are developed and created on papers and tested in theory. The work included in this thesis analyses parameters from a real life transit agency. This chapter then goes on to include a model developed by the author which can be used to dynamically attain a more holistic account of the total stray current and presents corrosion assessment of utilities and collection mat.

The modelling techniques presented here establish both static and dynamic modelling to overcome the limitations of the existing simulation models.

Based on the literature review, survey observations, and transit agency personnel interviews conducted during this research the following critical needs of the industry have been identified during this research:

- Implementation of improved rail insulation (track-to-earth) techniques
- Standardization of regular testing program for all transit agencies
- Standard testing methods for stray-current and their limiting measurements based on baseline survey
- Guidelines for acceptable stray current control
- Ongoing track maintenance program (keep rail track-bed areas clean and drained)
- Proper placement of substations along the track using traction power and stray current corrosion modelling
- Use of adequate rail cross section rail to achieve suitable rail resistivity
- Use of cross bonding and

- Effective use of collection mat and size of reinforcement

8.2 Stray Current Corrosion and its Isolation

The stray current corrosion occurs due to the mechanism of current transfer between metals and a conductive electrolyte such as concrete, soil and water. Stray current reactions can be considered as a special case in that the anode (point of current discharge) may be at a considerable distance from the cathode (point of current pick-up). The driving force accelerating this reaction over natural processes is the rail-to-earth voltage.

Stray current flows across a structure or pipeline are not unidirectional and frequently change as a function of train position and with the impact of regenerative braking. It is important to note that the corrosion reactions are not reversible and current pick-up does not reverse the corrosion effects of current discharge. In addition to the stray current corrosion there is also the possibility of natural corrosion. However, for reinforcement in good quality concrete, the natural rate of corrosion is insignificant.

The risk of stray current corrosion arising from the operation of dc powered transit system is difficult to eliminate completely. However, the design of dc traction power systems including stray current isolation and structures carrying the railways can significantly reduce the risk of corrosion both to the transit system structures and third party structures.

The most effective means of controlling the risk of stray current corrosion are identified in chapter 5 above and are summarized here:

- Design of traction supply circuits with low resistance
- Design of high track-to-earth resistance
- The use of floating earth systems
- Provisions to collect and constrain high proportions of current within the structure with an electrical path back to the return rail, e.g., stray current collector system or reinforcement mat.

Similarly, general methods to control corrosion on utility structures (in addition to rail system stray current control methods) include:

- Coating to insulate the line from earth
- Reduce electrical continuity of the buried structure
- Installing impressed current cathodic protection to counteract the stray current flow
- Install sacrificial anodes to provide a safe path for current to discharge (avoid locating anodes where current pickup occurs as stray current could be increased)
- Reduce the level of stray current being produced by the system

Using the simulation model for a floating earth system, Chapter 6 illustrates the importance of the various isolation and mitigation practices identified to reduce the level of stray current in a dc transit system. These mitigation parameters are then stressed in Chapter 7 where the model is used to calculate the total stray current leakage on a real transit system.

8.3 Potential Future Work

The work performed in this thesis includes the guidelines to perform stray current isolation and mitigation techniques supported by the modelling process, yet there are areas within this topic that need further development which include but are not limited to:

- **Interactive User Interface –** Development of a model that uses real time digital representation of physical and functional characteristics of the system. The software would allow users to define input parameters like nominal rail resistivity, track type, etc. to a real life transit system drawn in CAD which would then calculate the stray current performance of the transit system. This could also be tied into the train traction power modelling software. The software would follow a multi-step process and provide the user with output(s) to design the system for stray current leakage.
- **Modelling for Regeneration Braking –** Through a better interface to an electrical power modelling software more complicated scenarios like regenerative current (braking) could be modelled. The current model assumes that all the current to the train is supplied from the substation on the same track. However, in real dc transit systems a train from track 1 can potentially be receiving current from the regenerating (braking) current from the second track. This complicates the stray current calculation since now there is another current source for the train. A

simulation model that can account for the regeneration braking would help in calculating the stray current leakage.

- **Material Lost and Cost Impact –** The research carried out and the model produced under this thesis reveals the potential corrosion impact on the structure for different scenarios and the total stray current leakage. However, an additional key element missing is the potential cost of the stray current control. 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 the potential mitigation measure once the problem is identified on an existing system.

  A means to ascertain these costs would help the transit owners in making key decisions of providing the corrosion mitigation measure at the time of initial construction versus during the transit service. With the integration of traction power software, stray current model, and costing software at the design stage a holistic solution can be achieved for the stray current mitigation.

8.4 Achievements

The research has been presented in four conference papers including three at the Joint Rail Conference (JRC), one at the American Railway Engineering and Maintenance-of-Way Association (AREMA) meeting, and a paper in the Institute of Electrical and Electronics Engineers (IEEE) Electrification Magazine.

The author is also part of the IEEE Traction Power Substation Standards Subcommittee that is working on drafting the recommendations for grounding practices for dc powered transit systems and guidelines for Stray current corrosion control for dc transit system. This document is in draft shape and is being currently developed by a select team of subcommittee members including the author.

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1. S.A. Memon, S. Clark, A. Combs, “Installation of Rail Lubrication on Embedded Track”. AREMA Annual Proceedings 2010.
2. S. A. Memon, “Understanding Stray Current Mitigation, Testing and Maintenance on DC Powered Rail Transit Systems”, Proceedings of the 2013 Joint Rail Conference, April 15-18, 2013.
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Appendix A

Serial #	Question	Response from Transit Agencies				
	Transit Agency Name	**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 Name	**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 Name	**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 Name	**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 then 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 B

S. No.	Question				
	Transit Agency Name	**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	Transit Agency 4
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 Name	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	Its 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 Name	**Transit Agency 1**	**Transit Agency 2**	**Transit Agency 3**	**Transit Agency 4**
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
	Cost				
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 Name	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
	Summary				
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, ffice 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.