Model created in COMSOL Multiphysics 6.4

Stray Currents from a Train in a Light Rail Transit System

Introduction

Light rail transit (LRT) systems often utilize DC power for train propulsion. In these systems, trains operate with current fed from traction substations (TSS) through overhead lines and the rails usually serve as conductors for the returning current. Since the rails are more or less in contact with the surrounding soil, portions of the returning current can be stray. To avoid corrosion of adjacent metallic structures when building new railways, the stray currents often need to be considered.

This example models stray currents from a moving train in an LRT system and the resulting corrosion of a nearby pipe. The 3D domain surrounding the rails and the pipe features different soil conductivities. The impact of changed soil conductivities and pipe position is also investigated.

Model Definition

The model geometry is shown in Figure 1.

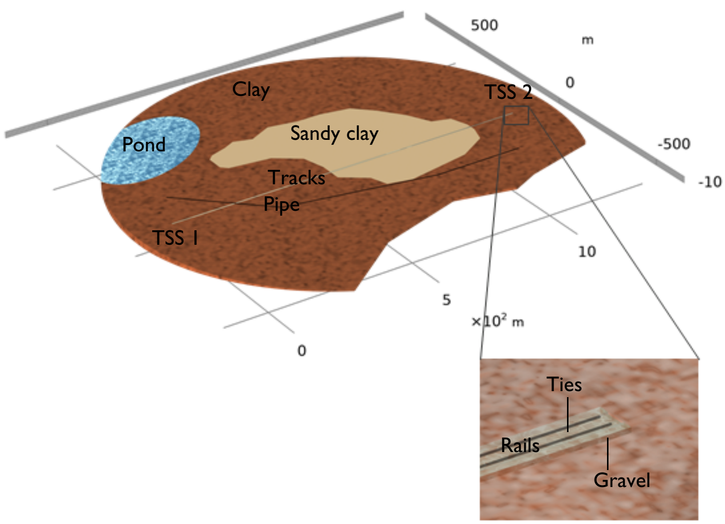

Figure 1: 3D model geometry.

Soil layers, tracks (rails sitting on ties and gravel), and a pipe are accounted for. The soil profile has a radius of 750 m and a depth confined by insulating rock. The pipe is positioned at a depth of 2.5 m. Start and end stations for the train are located near traction substations, denoted “TSS 1” and “TSS 2”, respectively. It takes 90 s for the train to travel between the stations. The distance between the two substations is 1.24 km.

The Cathodic Protection interface is used to solve for the electrolyte potential, ϕ_l (SI unit: V), over the 3D domains according to:

$$\begin{aligned}\mathbf{i}_l &= -\sigma_l \nabla \phi_l \\ \nabla \cdot \mathbf{i}_l &= 0\end{aligned} \tag{1}$$

where $\mathbf{i}_l$ (SI unit: A/m^2) is the electrolyte current density vector and σ_l (SI unit: S/m) is the electrolyte conductivity for the soil domain. **Electrolyte** nodes are used at each domain to set different electrolyte conductivities.

The rails and pipe are modeled using **Edge Electrode** nodes. At each node, the kinetics of the electrochemical reaction is prescribed as:

$$\mathbf{n} \cdot \mathbf{i}_l = f(\phi_{s,\text{ edge}} - \phi_{l,\text{ edge}}) \tag{2}$$

where $f(\phi_{s,\text{edge}} - \phi_{l,\text{edge}})$ is an interpolation function obtained form the experimental polarization data for steel, available in the **Corrosion** folder in the **Material Library**.

At the rail edges, the **Ohm's Law** electric potential model is defined. At the TSS 2 boundaries, an **Electric Potential** of 0 V (ground) is set. At the TSS 1 boundaries, an **Electrode Current** node is used to define the traction substation current-feed to the train. The feed is shared between the two traction substations and depends on train location. Consequently, the current at TSS 1, I_{tss1}, is defined as:

$$I_{\text{tss1}} = -I_{\text{train}}(t)\left(1 - \frac{\text{loc}_{\text{train}}(t)}{2L_{\text{rail}}}\right) \tag{3}$$

where the train propulsion current, I_{train}, and location, $\text{loc}_{\text{train}}$, are modeled using time-dependent interpolation functions (Figure 2). L_{rail} is the length of the rail between the two traction substations.

The train propulsion current is defined using an **External Current Source** node in the **Edge Electrode** node for the rails. The current source, $q_{1,\text{s}}$, is set up using the I_{train} and $\text{loc}_{\text{train}}$ function together with a **Gaussian Pulse** to model the current source where the train is located.

At the pipe edge, the electric potential model is set to floating potential with zero applied current, which indicates that the pipe is electrically not connected to anything and it will interact with the adjacent soil domain only through the electrochemical reactions occurring at the pipe surface.

Figure 2 shows the train propulsion current together with the current fed from each TSS with time. The location of the train is included as well and indicates where along the rails the propulsion current is drawn.

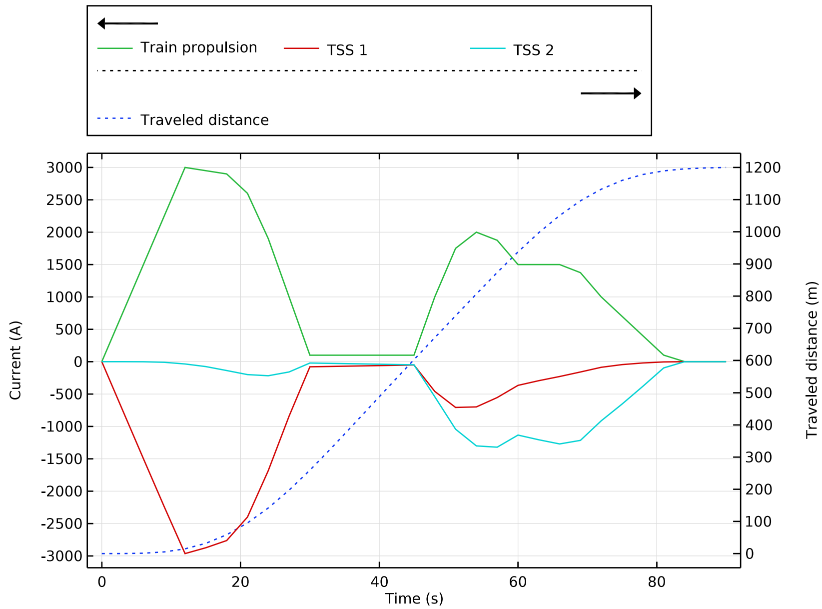

Figure 2: Left y-axis: Train propulsion current (I_{train}) and computed current feed from TSS 1 and TSS 2. Right x-axis: Train location (loc_{train}) in terms of traveled distance.

In Figure 3, the potential and pipe current-density distributions are shown for the soil profile when the train has passed more than half of the distance between the stations. Variations in potential are shown across the soil surface. At a distance of about 100 m from the train the potential drops rapidly. Where the pipe is positioned, the potential is nonuniform which explains the currents at the pipe and highlights that stray current from the train corrodes the pipe.

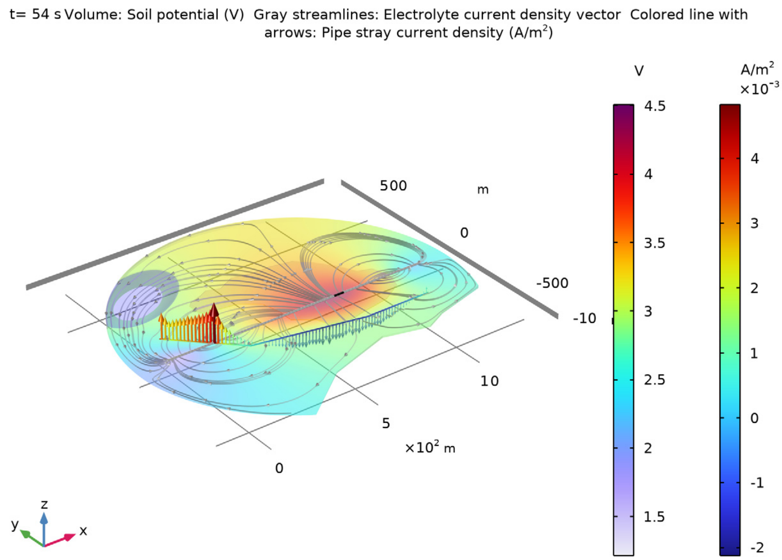

Figure 3: Results at 54 s. Potential distribution in the soil profile with gray arrowed streamlines indicating electrolyte current paths (at the same depth as the pipe). Colored arrows display the current density distribution at the pipe. The straight thick line in gray shows the rails with the black section indicating the location of the train.

Figure 3 displays the potential in one of the rails for different train locations. Note that the train moves solely between x-coordinates 0 to 1200 m and that the modeled rails are slightly longer. The potential gradients constitute the origin of the stray current.

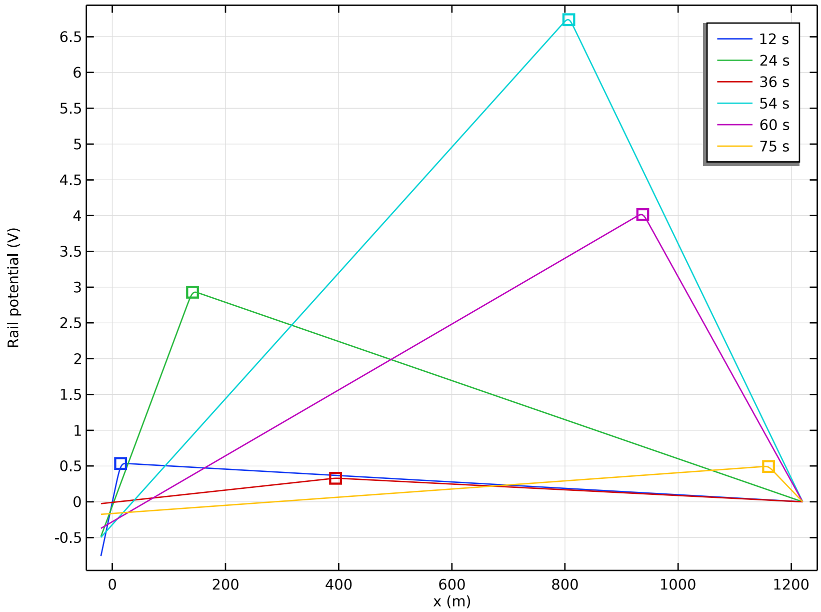

Figure 4: The potential in the upper rail for different times. Square marks the train location.

In Figure 5, the stray current densities show that larger potential gradients in the rail results in larger stray currents. Positive and negative current density values indicate exiting and entering current, respectively.

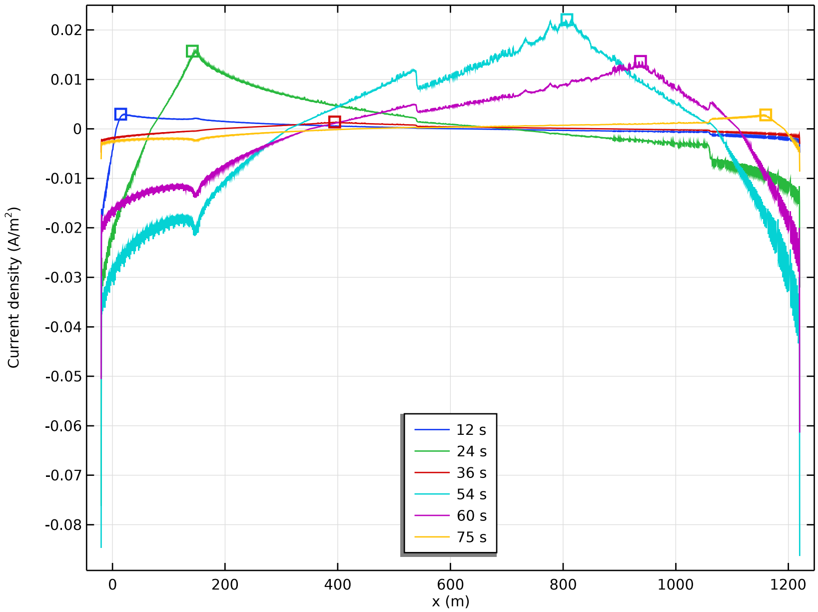

Figure 5: Stray current density at the upper rail for different times. Square marks the train location.

The current density at the pipe is seen in Figure 6. At 54 s, the train seems to induce the highest corrosion currents (> 0) at the pipe.

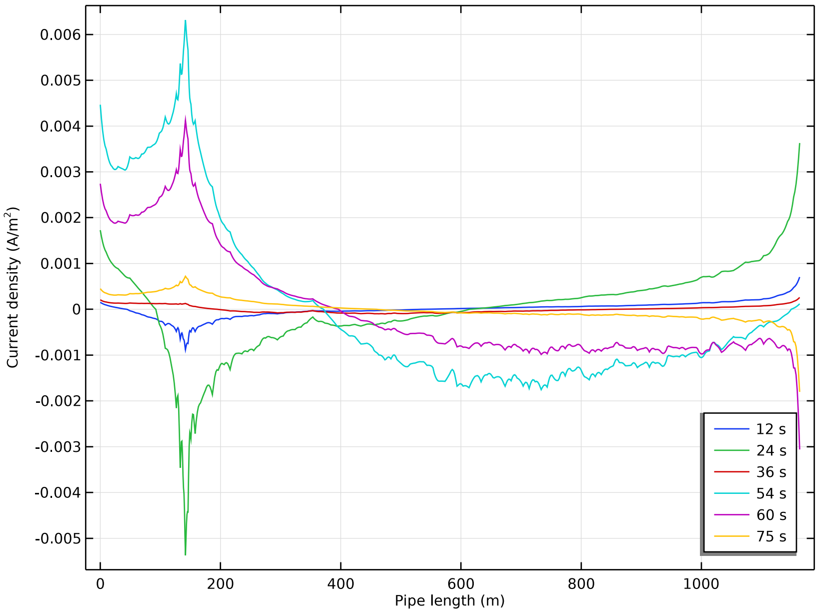

Figure 6: Current density at the pipe at different times.

The corrosion rate of the pipe is affected by the soil conditions and its position. The impact was simulated as well and is shown at 54 s in Figure 7. Repositioning the pipe mitigates corrosion more than changed soil resistivity.

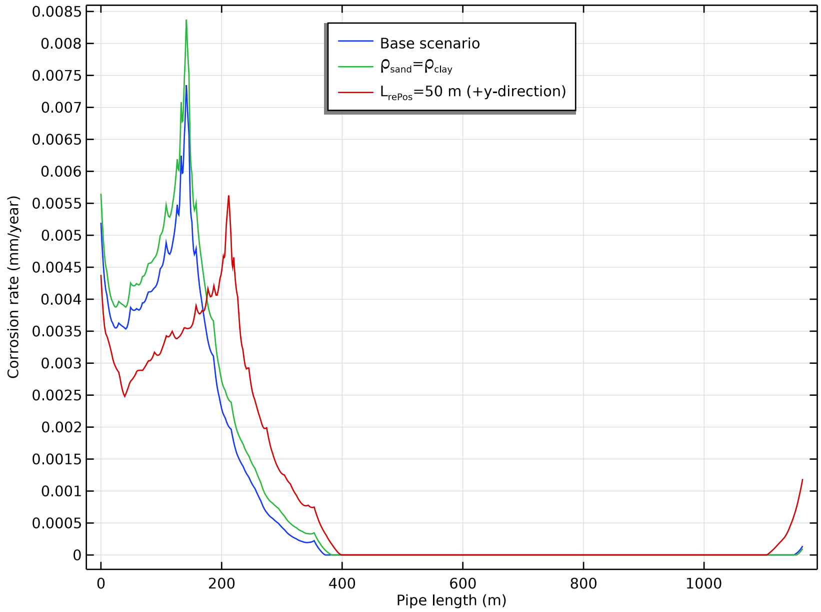

Figure 7: Corrosion rate at pipe at 54 s for three different scenarios.

Notes About the COMSOL Implementation

Since no processes in the model accumulate with time, a **Stationary** solver using an **Auxiliary sweep** with time as parameter can be used. This approach reduces the computation time.

References

1. Z. Cai, X. Zhang, and H. Cheng, “Evaluation of DC-Subway Stray Current Corrosion With Integrated Multi-Physical Modeling and Electrochemical Analysis,” *IEEE Access*, vol. 7, p. 168404, 2019.

2. S. Aatif, H. Hu, F. Rafiq, and Z. He, “Analysis of rail potential and stray current in MVDC railway electrification system,” *Railway Engineering Science*, vol. 29, p. 394, 2019.

3. G. Du, D. Zhang, G. Li, C. Wang, and J. Liu, “Evaluation of Rail Potential Based on Power Distribution in DC Traction Power Systems,” *Energies*, vol. 9, p. 729, 2016.

Application Library path: `Corrosion_Module/General_Corrosion/stray_current_train`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.

2 In the **Select Physics** tree, select **Electrochemistry** > **Cathodic Protection (cp)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies** > **Stationary**.

6 Click **Done**.

GLOBAL DEFINITIONS

Load the model parameters from a text file.

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `stray_current_train_parameters.txt`.

Use a **Gaussian Pulse** function to describe the shape of the train positioning at the rails. Set the integrated value to 1 and the standard deviation value to 4 for a simpler and more realistic train representation.

Gaussian Pulse - Shape Train Positioning

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global** > **Gaussian Pulse**.

2 In the **Settings** window for **Gaussian Pulse**, type `Gaussian Pulse - Shape Train Positioning` in the **Label** text field.

3 In the **Function name** text field, type `shape_train`.

4 Locate the **Parameters** section. In the **Standard deviation** text field, type `4`.

The train propulsion current with travel time is imported using an **Interpolation** function.

Interpolation - Train Propulsion Current

1 In the **Home** toolbar, click f(x) **Functions** and choose **Global** > **Interpolation**.

2 In the **Settings** window for **Interpolation**, type `Interpolation - Train Propulsion Current` in the **Label** text field.

3 Locate the **Definition** section. In the **Function name** text field, type `I_train`.

4 Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `stray_current_train_propulsion_current.txt`.

6 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
I_train	A

7 In the **Argument** table, enter the following settings:

Argument	Unit
t	s

The train location with travel time is also imported using an **Interpolation** function.

Interpolation - Train Location

1 In the **Home** toolbar, click f(x) **Functions** and choose **Global** > **Interpolation**.

2 In the **Settings** window for **Interpolation**, type `Interpolation - Train Location` in the **Label** text field.

3 Locate the **Definition** section. In the **Function name** text field, type `loc_train`.

4 Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `stray_current_train_location.txt`.

6 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
loc_train	m

7 In the **Argument** table, enter the following settings:

Argument	Unit
t	s

GEOMETRY 1

Import the geometry of the tracks and soil profile from a geometry file.

Import 1 (imp1)

1 In the **Geometry** toolbar, click **Import**.

2 In the **Settings** window for **Import**, locate the **Source** section.

3 Click **Browse**.

4 Browse to the model's Application Libraries folder and double-click the file `stray_current_train_geometry.mphbin`.

5 Click **Import**.

Draw the pipe in the imported geometry. Use parameter L_rePos that easily can be changed to reposition the pipe.

Work Plane - Pipe

1 In the **Geometry** toolbar, click **Work Plane**.

2 In the **Settings** window for **Work Plane**, type `Work Plane - Pipe` in the **Label** text field.

3 Locate the **Plane Definition** section. In the **z-coordinate** text field, type `z_pipe`.

Work Plane - Pipe (wp1) > Plane Geometry

In the **Model Builder** window, click **Plane Geometry**.

Work Plane - Pipe (wp1) > Polygon 1 (pol1)

1 In the **Work Plane** toolbar, click **Polygon**.

2 In the **Settings** window for **Polygon**, locate the **Object Type** section.

3 From the **Type** list, choose **Open curve**.

4 Locate the **Coordinates** section. In the table, enter the following settings:

xw (m)	yw (m)
50	100+L_rePos
300	-150+L_rePos
800	-250+L_rePos
1100	-250+L_rePos

5 In the **Home** toolbar, click **Build All**.

Disable the analysis of the geometry as the remaining small geometric details are needed.

6 In the **Model Builder** window, click **Geometry 1**.

7 In the **Settings** window for **Geometry**, locate the **Cleanup** section.

8 Clear the **Automatic detection of small details** checkbox.

DEFINITIONS

Railway Ties

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Railway Ties` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `4,7,9` in the **Selection** text field.

5 Click **OK**.

Gravel

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Gravel` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `3,6,8` in the **Selection** text field.

5 Click **OK**.

Clay

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Clay` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `1` in the **Selection** text field.

5 Click **OK**.

Pond

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Pond` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `2` in the **Selection** text field.

5 Click **OK**.

Sandy Clay

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Sandy Clay` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `5` in the **Selection** text field.

5 Click **OK**.

Pipe

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Pipe` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Edge**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `34,55,135` in the **Selection** text field.

6 Click **OK**.

Rails

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Rails` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Edge**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `30,31,96,98,177,179` in the **Selection** text field.

6 Click **OK**.

Upper Rail

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Upper Rail` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Edge**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `31,98,179` in the **Selection** text field.

6 Click **OK**.

Steel

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Steel` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Edge**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `30,31,34,55,96,98,135,177,179` in the **Selection** text field.

6 Click **OK**.

TSS 1

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `TSS 1` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Point**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `14,15` in the **Selection** text field.

6 Click **OK**.

TSS 2

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `TSS 2` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Point**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `114,115` in the **Selection** text field.

6 Click **OK**.

Add some **Integration** operators for postprocessing.

Integration - TSS 1

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 In the **Settings** window for **Integration**, type `Integration - TSS 1` in the **Label** text field.

3 In the **Operator name** text field, type `intop_tss1`.

4 Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Point**.

5 From the **Selection** list, choose **TSS 1**.

Integration - TSS 2

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 In the **Settings** window for **Integration**, type `Integration - TSS 2` in the **Label** text field.

3 In the **Operator name** text field, type `intop_tss2`.

4 Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Point**.

5 From the **Selection** list, choose **TSS 2**.

Define a maximum operator at the upper rail to be used for postprocessing.

Maximum - Upper Rail

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Maximum**.

2 In the **Settings** window for **Maximum**, type `Maximum - Upper Rail` in the **Label** text field.

3 In the **Operator name** text field, type `maxop_uprail`.

4 Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Edge**.

5 From the **Selection** list, choose **Upper Rail**.

Define variables at various locations in the geometry.

Variables - Rails

1 In the **Home** toolbar, click a= **Variables** and choose **Local Variables**.

2 In the **Settings** window for **Variables**, type `Variables - Rails` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Edge**.

4 From the **Selection** list, choose **Rails**.

5 Locate the **Variables** section. In the table, enter the following settings:

Name	Expression	Unit	Description
qls_rail	I_train(t_train)*shape_train(x/1[m]-loc_train(t_train)/1[m])/2[m]	A/m	Train current source along each rail

Variables - Pipe

1 In the **Home** toolbar, click a= **Variables** and choose **Local Variables**.

2 In the **Settings** window for **Variables**, type `Variables - Pipe` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Edge**.

4 From the **Selection** list, choose **Pipe**.

5 Locate the **Variables** section. In the table, enter the following settings:

Name	Expression	Unit	Description
dr_rate	cp.iloc_er1/F_const/ ro_pipe/2*M_pipe* (cp.iloc_er1>0)		Corrosion rate on pipe

Variables - TSS 1

1 In the **Home** toolbar, click **Variables** and choose **Local Variables**.

2 In the **Settings** window for **Variables**, type `Variables - TSS 1` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Point**.

4 From the **Selection** list, choose **TSS 1**.

5 Locate the **Variables** section. In the table, enter the following settings:

Name	Expression	Unit	Description
I_tss1	-I_train(t_train)*(1- loc_train(t_train)/ L_rail)/2	A	Total current at each rail at traction substation 1

Variables - TSS 2

1 In the **Home** toolbar, click **Variables** and choose **Local Variables**.

2 In the **Settings** window for **Variables**, type `Variables - TSS 2` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Point**.

4 From the **Selection** list, choose **TSS 2**.

5 Locate the **Variables** section. In the table, enter the following settings:

Name	Expression	Unit	Description
I_tss2	-cp.Is_edgex*cp.A		Total current at each rail at traction substation 2

Add steel in soil from the **Material Library** for the metallic objects (rails and pipe).

ADD MATERIAL

1 In the **Materials** toolbar, click **Add Material** to open the **Add Material** window.

2 Go to the **Add Material** window.

3 In the tree, select **Corrosion** > **Iron Alloys (Steels)** > **Q235 steel in soil**.

4 Click the **Add to Component** button in the window toolbar.

5 In the **Materials** toolbar, click **Add Material** to close the **Add Material** window.

Set up the physics. Start with the conductivities in each material.

CATHODIC PROTECTION (CP)

Electrolyte - Clay

1 In the **Settings** window for **Electrolyte**, type `Electrolyte - Clay` in the **Label** text field.

2 Locate the **Electrolyte** section. From the σ_l list, choose **User defined**. In the associated text field, type `1/rho_clay`.

Electrolyte - Pond

1 In the **Physics** toolbar, click **Domains** and choose **Electrolyte**.

2 In the **Settings** window for **Electrolyte**, type `Electrolyte - Pond` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Pond**.

4 Locate the **Electrolyte** section. From the σ_l list, choose **User defined**. In the associated text field, type `1/rho_pond`.

Electrolyte - Sandy Clay

1 In the **Physics** toolbar, click **Domains** and choose **Electrolyte**.

2 In the **Settings** window for **Electrolyte**, type `Electrolyte - Sandy Clay` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Sandy Clay**.

4 Locate the **Electrolyte** section. From the σ_l list, choose **User defined**. In the associated text field, type `1/rho_sand`.

Electrolyte - Ties

1 In the **Physics** toolbar, click **Domains** and choose **Electrolyte**.

2 In the **Settings** window for **Electrolyte**, type `Electrolyte - Ties` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Railway Ties**.

4 Locate the **Electrolyte** section. From the σ_l list, choose **User defined**. From the list, choose **Diagonal**.

Since the ties are discontinuous in the x direction (ties separated by gravel), define an anisotropic conductivity.

5 Specify the σ_l matrix as

`1/rho_tiex`	`0`	`0`
`0`	`1/rho_tie`	`0`
`0`	`0`	`1/rho_tie`

Electrolyte - Gravel

1 In the **Physics** toolbar, click **Domains** and choose **Electrolyte**.

2 In the **Settings** window for **Electrolyte**, type `Electrolyte - Gravel` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Gravel**.

4 Locate the **Electrolyte** section. From the σ_l list, choose **User defined**. In the associated text field, type `1/rho_gravel`.

Use the **Edge Electrode** node to define the rail properties.

Edge Electrode - Rails

1 In the **Physics** toolbar, click **Edges** and choose **Edge Electrode**.

2 In the **Settings** window for **Edge Electrode**, type `Edge Electrode - Rails` in the **Label** text field.

3 Locate the **Edge Selection** section. From the **Selection** list, choose **Rails**.

4 Locate the **Edge Electrode Properties** section. In the r_{edge} text field, type `r_rail`.

The insulation of the rail can be adjusted in the **Film Resistance** section.

5 Click to expand the **Film Resistance** section. From the **Film resistance** list, choose **Surface resistance**.

6 In the R_{film} text field, type `R_railins`.

Electrode Reaction 1

Choose the electrode kinetics from the material that was selected earlier.

1 In the **Model Builder** window, click **Electrode Reaction 1**.

2 In the **Settings** window for **Electrode Reaction**, locate the **Equilibrium Potential** section.

3 From the E_{eq} list, choose **From material**.

4 Locate the **Electrode Kinetics** section. From the $i_{\text{loc,expr}}$ list, choose **From material**.

The electrode current is set at TSS 1 and ground at TSS 2.

Edge Electrode - Rails

In the **Model Builder** window, click **Edge Electrode - Rails**.

Electrode Current - TSS 1

1 In the **Physics** toolbar, click **Attributes** and choose **Electrode Current**.
2 In the **Settings** window for **Electrode Current**, type `Electrode Current - TSS 1` in the **Label** text field.
3 Locate the **Point Selection** section. From the **Selection** list, choose **TSS 1**.
4 Locate the **Electrode Current** section. In the $I_{s,total}$ text field, type `I_tss1`.

Edge Electrode - Rails

In the **Model Builder** window, click **Edge Electrode - Rails**.

Electric Potential - TSS 2

1 In the **Physics** toolbar, click **Attributes** and choose **Electric Potential**.
2 In the **Settings** window for **Electric Potential**, type `Electric Potential - TSS 2` in the **Label** text field.
3 Locate the **Point Selection** section. From the **Selection** list, choose **TSS 2**.

Use the **External Current Source** to define the current locally with train location.

Edge Electrode - Rails

In the **Model Builder** window, click **Edge Electrode - Rails**.

External Current Source - Train

1 In the **Physics** toolbar, click **Attributes** and choose **External Current Source**.
2 In the **Settings** window for **External Current Source**, type `External Current Source - Train` in the **Label** text field.
3 Locate the **External Current Source** section. In the $q_{1,s}$ text field, type `qls_rail`.

Add an additional **Edge Electrode** node and define the conditions at the pipe.

Edge Electrode - Pipe

1 In the **Physics** toolbar, click **Edges** and choose **Edge Electrode**.
2 In the **Settings** window for **Edge Electrode**, type `Edge Electrode - Pipe` in the **Label** text field.
3 Locate the **Edge Selection** section. From the **Selection** list, choose **Pipe**.
4 Locate the **Edge Electrode Properties** section. In the r_{edge} text field, type `r_pipe`.
5 Locate the **Electric Potential** section. From the **Electric potential model** list, choose **Floating potential**.

Electrode Reaction 1

1 In the **Model Builder** window, click **Electrode Reaction 1**.

2 In the **Settings** window for **Electrode Reaction**, locate the **Equilibrium Potential** section.

3 From the E_{eq} list, choose **From material**.

4 Locate the **Electrode Kinetics** section. From the $i_{loc,expr}$ list, choose **From material**.

Add the conductivity of steel in the selected material.

MATERIALS

Q235 steel in soil (mat1)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Materials** click **Q235 steel in soil (mat1)**.

2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Edge**.

4 From the **Selection** list, choose **Steel**.

5 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	sigma_steel	S/m	Basic

Define a mesh that refines the meshes at and near the rails and pipe.

MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 In the table, clear the **Use** checkbox for **Geometric Analysis, Detail Size**.

4 Locate the **Sequence Type** section. From the list, choose **User-controlled mesh**.

Size

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Mesh 1** click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Coarse**.

4 Click **Build All**.

Size 1

1 In the **Model Builder** window, right-click **Free Tetrahedral 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 From the **Selection** list, choose **Gravel**.

Size 2

1 Right-click **Free Tetrahedral 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Edge**.

4 From the **Selection** list, choose **Pipe**.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Maximum element size** checkbox. In the associated text field, type 10.

Size 3

1 Right-click **Free Tetrahedral 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 From the **Selection** list, choose **Railway Ties**.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Maximum element size** checkbox. In the associated text field, type 3.

8 Select the **Maximum element size** checkbox. In the associated text field, type 2.

9 Select the **Resolution of narrow regions** checkbox. In the associated text field, type 1.

10 Click **Build All**.

To investigate different corrosion mitigation approaches add a **Parametric sweep**. Use the **Auxiliary sweep** in the **Stationary** study step to compute the positions of the train during its 90 s journey between the stations.

STUDY 1

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	**Parameter value list**	**Parameter unit**
L_rePos (Repositioning distance pipe)	`0 0 50`	`m`

5 Click **Add**.

6 In the table, enter the following settings:

Parameter name	**Parameter value list**	**Parameter unit**
rho_sand (Resistivity of sandy clay)	`400 50 400`	Ω*m

Step 1: Stationary

1 In the **Model Builder** window, click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, click to expand the **Study Extensions** section.

3 Select the **Auxiliary sweep** checkbox.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	**Parameter value list**	**Parameter unit**
t_train (Train traveling time)	`range(0,3,90)`	`s`

6 In the **Home** toolbar, click **Compute**.

RESULTS

A few plots are added by default. The following steps shows how the figures in the model documentation are made.

Start with the plot that shows the distributions in current and potential in the soil profile (Figure 3).

Potential and Current Density Distribution (cp)

1 In the **Model Builder** window, under **Results** click **Electrolyte Current Density (cp)**.

2 In the **Settings** window for **3D Plot Group**, type `Potential and Current Density Distribution (cp)` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter value (t_train (s))** list, choose **54**.

4 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Volume: Soil potential (V)  Gray streamlines: Electrolyte current density vector  Colored line with arrows: Pipe stray current density (A/m<sup>2</sup>)`.

6 In the **Parameter indicator** text field, type `t= eval(t_train) s`.

7 Locate the **Plot Settings** section. Clear the **Plot dataset edges** checkbox.

8 Locate the **Color Legend** section. Select the **Show units** checkbox.

Volume 1

In the **Potential and Current Density Distribution (cp)** toolbar, click **Volume**.

Streamline 1

In the **Model Builder** window, right-click **Streamline 1** and choose **Delete**.

Volume - Soil potential

1 In the **Settings** window for **Volume**, type `Volume - Soil potential` in the **Label** text field.

2 Locate the **Coloring and Style** section. From the **Color table** list, choose **Prism**.

Selection 1

1 In the **Potential and Current Density Distribution (cp)** toolbar, click **Selection**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 From the **Selection** list, choose **Clay**.

Volume - Soil potential

In the **Model Builder** window, click **Volume - Soil potential**.

Transparency 1

1 In the **Potential and Current Density Distribution (cp)** toolbar, click **Transparency**.

2 In the **Settings** window for **Transparency**, locate the **Transparency** section.

3 Find the **Transparency** subsection. In the **Transparency** text field, type `0.7`.

Potential and Current Density Distribution (cp)

In the **Potential and Current Density Distribution (cp)** toolbar, click **Line**.

Line - Train Position

1 In the **Settings** window for **Line**, type `Line - Train Position` in the **Label** text field.

2 Locate the **Expression** section. In the **Expression** text field, type `qls_rail>1e-6`.

3 Locate the **Coloring and Style** section. From the **Line type** list, choose **Tube**.

4 Select the **Radius scale factor** checkbox. In the associated text field, type `4`.

5 Clear the **Rounded end caps** checkbox.

6 From the **Coloring** list, choose **Gradient**.

7 From the **Top color** list, choose **Black**.

8 From the **Bottom color** list, choose **Gray**.

9 Clear the **Color legend** checkbox.

Potential and Current Density Distribution (cp)

In the **Potential and Current Density Distribution (cp)** toolbar, click **Surface**.

Surface - Pond

1 In the **Settings** window for **Surface**, type `Surface - Pond` in the **Label** text field.

2 Locate the **Expression** section. In the **Expression** text field, type `1`.

3 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.

4 From the **Color** list, choose **Blue**.

Selection 1

1 In the **Potential and Current Density Distribution (cp)** toolbar, click **Selection**.

2 Select Boundary 7 only.

Surface - Pond

In the **Model Builder** window, click **Surface - Pond**.

Transparency 1

1 In the **Potential and Current Density Distribution (cp)** toolbar, click **Transparency**.

2 In the **Settings** window for **Transparency**, locate the **Transparency** section.

3 Find the **Transparency** subsection. In the **Transparency** text field, type `0.8`.

4 Find the **Fresnel transmittance** subsection. In the **Fresnel transmittance** text field, type `1`.

Surface - Sand

1 Right-click **Surface - Pond** and choose **Duplicate**.

2 In the **Settings** window for **Surface**, type `Surface - Sand` in the **Label** text field.

3 Locate the **Coloring and Style** section. From the **Color** list, choose **Custom**.

4 On Windows, click the colored bar underneath, or — if you are running the cross-platform desktop — the **Color** button.

5 Click **Define custom colors**.

6 Set the RGB values to 196, 106, and 72, respectively.

7 Click **Add to custom colors**.

8 Click **Show color palette only** or **OK** on the cross-platform desktop.

Selection 1

1. In the **Model Builder** window, expand the **Surface - Sand** node, then click **Selection 1**.
2. In the **Settings** window for **Selection**, locate the **Selection** section.
3. Click to select the **Activate Selection** toggle button.
4. Select Boundaries 28 and 40 only.

Transparency 1

1. In the **Model Builder** window, click **Transparency 1**.
2. In the **Settings** window for **Transparency**, locate the **Transparency** section.
3. Find the **Transparency** subsection. In the **Transparency** text field, type `0.85`.
4. Find the **Fresnel transmittance** subsection. In the **Fresnel transmittance** text field, type `0`.

Potential and Current Density Distribution (cp)

In the **Potential and Current Density Distribution (cp)** toolbar, click **Line**.

Line - Pipe Stray Current Density

1. In the **Settings** window for **Line**, type `Line - Pipe Stray Current Density` in the **Label** text field.
2. Click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Cathodic Protection** > **Electrode kinetics** > **cp.iloc_er1 - Local current density - A/m²**.
3. Locate the **Coloring and Style** section. From the **Line type** list, choose **Tube**.
4. Select the **Radius scale factor** checkbox. In the associated text field, type `3`.

Selection 1

1. In the **Potential and Current Density Distribution (cp)** toolbar, click **Selection**.
2. In the **Settings** window for **Selection**, locate the **Selection** section.
3. From the **Selection** list, choose **Pipe**.

Potential and Current Density Distribution (cp)

In the **Potential and Current Density Distribution (cp)** toolbar, click **Arrow Line**.

Arrow Line 1

1. In the **Settings** window for **Arrow Line**, locate the **Expression** section.
2. In the **X-component** text field, type `0`.
3. In the **Y-component** text field, type `0`.

4 In the **Z-component** text field, type `cp.iloc_er1`.

5 Locate the **Arrow Positioning** section. In the **Number of arrows** text field, type `80`.

6 Locate the **Coloring and Style** section.

7 Select the **Scale factor** checkbox. In the associated text field, type `40000`.

Selection 1

1 In the **Potential and Current Density Distribution (cp)** toolbar, click **Selection**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 From the **Selection** list, choose **Pipe**.

Arrow Line 1

In the **Model Builder** window, click **Arrow Line 1**.

Color Expression 1

1 In the **Potential and Current Density Distribution (cp)** toolbar, click **Color Expression**.

2 In the **Settings** window for **Color Expression**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Cathodic Protection** > **Electrode kinetics** > **cp.iloc_er1 - Local current density - A/m²**.

3 Locate the **Coloring and Style** section. Clear the **Color legend** checkbox.

Potential and Current Density Distribution (cp)

In the **Potential and Current Density Distribution (cp)** toolbar, click **More Plots** and choose **Streamline Multislice**.

Streamline Multislice 1

1 In the **Settings** window for **Streamline Multislice**, locate the **Multiplane Data** section.

2 Find the **X-planes** subsection. In the **Planes** text field, type `0`.

3 Find the **Y-planes** subsection. In the **Planes** text field, type `0`.

4 Find the **Z-planes** subsection. From the **Entry method** list, choose **Coordinates**.

5 In the **Coordinates** text field, type `z_pipe`.

6 Locate the **Streamline Positioning** section. In the **Points** text field, type `70`.

7 Locate the **Coloring and Style** section. Find the **Point style** subsection. From the **Type** list, choose **Arrow**.

8 From the **Color** list, choose **Gray**.

9 In the **Potential and Current Density Distribution (cp)** toolbar, click **Plot**.

Current

1 In the **Results** toolbar, click **1D Plot Group**.

Continue with the currents at the rail and traction substations plot (Figure 2).

2 In the **Settings** window for **1D Plot Group**, type `Current` in the **Label** text field.
3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.
4 From the **Parameter selection (L_rePos, rho_sand)** list, choose **First**.
5 Click to expand the **Title** section. From the **Title type** list, choose **None**.
6 Locate the **Plot Settings** section. Select the **Two y-axes** checkbox.
7 Select the **x-axis label** checkbox. In the associated text field, type `Time (s)`.
8 Select the **y-axis label** checkbox. In the associated text field, type `Current (A)`.
9 Select the **Secondary y-axis label** checkbox. In the associated text field, type `Traveled distance (m)`.
10 Locate the **Legend** section. From the **Layout** list, choose **Outside graph axis area**.
11 From the **Position** list, choose **Top**.

Global 1

1 In the **Current** toolbar, click **Global**.
2 In the **Settings** window for **Global**, locate the **y-Axis** section.
3 Select the **Plot on secondary y-axis** checkbox.
4 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`loc_train(t_train)`	`m`	`Interpolation - Train Location`

5 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dotted**.
6 Click to expand the **Legends** section. From the **Legends** list, choose **Manual**.
7 In the table, enter the following settings:

Legends
`Traveled distance`

Current

In the **Current** toolbar, click **Global**.

Global 2

1 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

2 In the table, enter the following settings:

Expression	Unit	Description
`I_train(t_train)`	`A`	`Interpolation - Train Propulsion Current`
`intop_tss1(I_tss1)`	`A`	`Integration - TSS 1`
`intop_tss2(I_tss2)`	`A`	`Integration - TSS 2`

3 Locate the **Legends** section. From the **Legends** list, choose **Manual**.

4 In the table, enter the following settings:

Legends
`Train propulsion`
`TSS 1`
`TSS 2`

5 In the **Current** toolbar, click **Plot**.

Rail Potential

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

Continue with the (upper) rail potential plot (Figure 4).

2 In the **Settings** window for **1D Plot Group**, type `Rail Potential` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.

4 From the **Parameter selection (L_rePos, rho_sand)** list, choose **First**.

5 From the **Parameter selection (t_train)** list, choose **From list**.

6 In the **Parameter values (t_train (s))** list, choose **12**, **24**, **36**, **54**, **60**, and **75**.

7 Locate the **Title** section. From the **Title type** list, choose **None**.

8 Locate the **Plot Settings** section.

9 Select the **x-axis label** checkbox. In the associated text field, type `x (m)`.

10 Select the **y-axis label** checkbox. In the associated text field, type `Rail potential (V)`.

Line Graph 1

1 In the **Rail Potential** toolbar, click **Line Graph**.

2 In the **Settings** window for **Line Graph**, locate the **Selection** section.

3 From the **Selection** list, choose **Upper Rail**.

4 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Cathodic Protection** > **Secondary Current Distribution (Edge electrode)** > **cp.phis_edge - Electric potential - V**.

5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `x`.

7 Click to expand the **Legends** section. Select the **Show legends** checkbox.

8 From the **Legends** list, choose **Manual**.

9 In the table, enter the following settings:

Legends
12 s
24 s
36 s
54 s
60 s
75 s

Line Graph 2

1 Right-click **Line Graph 1** and choose **Duplicate**.

2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `maxop_uprail(cp.phis_edge)`.

4 Locate the **x-Axis Data** section. In the **Expression** text field, type `loc_train(t_train)`.

5 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.

6 From the **Color** list, choose **Cycle (reset)**.

7 From the **Width** list, choose **2**.

8 Find the **Line markers** subsection. From the **Marker** list, choose **Square**.

9 Locate the **Legends** section. Clear the **Show legends** checkbox.

10 In the **Rail Potential** toolbar, click **Plot**.

Stray Current Density at Rail

1 In the **Model Builder** window, right-click **Rail Potential** and choose **Duplicate**.

Continue with the stray currents at the (upper) rail plot (Figure 5).

2 In the **Settings** window for **1D Plot Group**, type `Stray Current Density at Rail` in the **Label** text field.

3 Locate the **Plot Settings** section. In the **y-axis label** text field, type Current density (A/m²).

4 Locate the **Legend** section. From the **Position** list, choose **Lower middle**.

Line Graph 1

1 In the **Model Builder** window, expand the **Stray Current Density at Rail** node, then click **Line Graph 1**.

2 In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Cathodic Protection** > **Electrode kinetics** > **cp.iloc_er1 - Local current density - A/m^2**.

Line Graph 2

1 In the **Model Builder** window, click **Line Graph 2**.

2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `maxop_uprail(cp.iloc_er1)`.

4 In the **Stray Current Density at Rail** toolbar, click **Plot**.

Current Density at Pipe

1 In the **Model Builder** window, right-click **Stray Current Density at Rail** and choose **Duplicate**.

Continue with the stray current at the pipe plot (Figure 6).

2 In the **Settings** window for **1D Plot Group**, type `Current Density at Pipe` in the **Label** text field.

3 Locate the **Plot Settings** section. In the **x-axis label** text field, type `Pipe length (m)`.

4 Locate the **Legend** section. From the **Position** list, choose **Lower right**.

Line Graph 1

1 In the **Model Builder** window, expand the **Current Density at Pipe** node, then click **Line Graph 1**.

2 In the **Settings** window for **Line Graph**, locate the **Selection** section.

3 From the **Selection** list, choose **Pipe**.

4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Arc length**.

Line Graph 2

In the **Model Builder** window, right-click **Line Graph 2** and choose **Delete**.

Line Graph 1

In the **Current Density at Pipe** toolbar, click **Plot**.

Comparison - Corrosion Rate on Pipe at 54 s

1 In the **Model Builder** window, right-click **Current Density at Pipe** and choose **Duplicate**.

Continue with the plot that compares corrosion rates at the pipe (Figure 7).

2 In the **Settings** window for **1D Plot Group**, type `Comparison - Corrosion Rate on Pipe at 54 s` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter selection (L_rePos, rho_sand)** list, choose **All**.

4 In the **Parameter values (t_train (s))** list box, select **54**.

5 Locate the **Plot Settings** section. In the **y-axis label** text field, type `Corrosion rate (mm/year)`.

6 Locate the **Legend** section. From the **Position** list, choose **Upper middle**.

Line Graph 1

1 In the **Model Builder** window, expand the **Comparison - Corrosion Rate on Pipe at 54 s** node, then click **Line Graph 1**.

2 In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Definitions > Variables > dr_rate - Corrosion rate on pipe - m/s**.

3 Locate the **y-Axis Data** section. From the **Unit** list, choose **mm/yr**.

4 Locate the **Legends** section. In the table, enter the following settings:

Legends
Base scenario
\rho _{sand}=\rho _{clay}
L_{rePos}=50 m (+y-direction)

5 In the **Comparison - Corrosion Rate on Pipe at 54 s** toolbar, click **Plot**.

Some of the default plots can be removed since these show little additional information.

Electrode Potential with Respect to Adjacent Reference (cp), Electrolyte Potential (cp)

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **Electrolyte Potential (cp)** and **Electrode Potential with Respect to Adjacent Reference (cp)**.

2 Right-click and choose **Delete**.

Use the **Animation** functionality to visualize the stray currents from the moving train better.

Animation 1

1 In the **Results** toolbar, click **Animation** and choose **Player**.

2 In the **Settings** window for **Animation**, click to expand the **Frames** section.

3 Click the **Play** button in the **Graphics** toolbar.