Preface

This document is part of a series of instruction manuals, which can be used as guidelines for applying the Train Operations Model (TOM) to rail systems throughout the world. In this connotation, rail system definition includes main line railroads, heavy and light rail, trolleybuses, high-speed rail and MAGLEV and people movers.

There are several manuals in the series:

Volume 1 – An Introduction to the Instruction Manual for Applying the TOM
Volume 2 – Instruction Manual for Applying the TOM to Transit Systems DC Electric – English Units
Volume 3 – Instruction Manual for Applying the TOM to Transit Systems DC Electric – Metric Units
Volume 4 – Instruction Manual for Applying the TOM to Transit Systems AC Electric – English Units
Volume 5 – Instruction Manual for Applying the TOM to Transit Systems AC Electric – Metric Units
Volume 6 – Instruction Manual for Applying the TOM to Railroads Fueled – English Units
Volume 7 – Instruction Manual for Applying the TOM to Railroads Fueled – Metric Units
Volume 8 – Instruction Manual for Applying the TOM to Rail Systems; Technology Aspects
Volume 9 – Instruction Manual for Procedures and Shortcuts in the TOM
Volume 10 – Instruction Manual for Including the Return Circuit in Electric Rail Systems
Volume 11 - Instruction Manual Exercising the AC Drive Model
Volume 12 – Instruction Manual DC Electric Power System Methodology
Volume 13 – Instruction Manual AC Electric Power System Methodology
Volume 14 – Instruction Manual Exercising the Rail Voltage Model for DC Traction Systems

Volumes 2-7 cover nearly all transit systems and railroads in the world.

This instruction manual is Volume 14.

These volumes are unprotected. Thus the user is free to make notes or rewrite sections according to his preferences.

The primary purpose for using the TOM is evaluation. The evaluation generally takes the form of a study, with certain objectives, which may or may not be well defined. As the study is conducted, new objectives may result, because of unanticipated results. Within the framework of evaluation, designs may be modified and further evaluated, so that in this sense, the TOM may be considered a design tool.

The TOM is used together with other standard software, such as Microsoft Office (in particular, WORD, EXCEL and POWERPOINT). This combined package is most effective in assembling client data as well as presenting results. In some instances, the TOM interacts directly with these office programs, while in other cases; the user handles the office packages directly.
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INTRODUCTION

The Train Operations Model (TOM)© Version 2.5 in the year 2000, included a Rail Voltage Model at the request of one of the licensees. The method used is now referred as the Old Method. It is explained below.

The Rail Voltage Model (RVM) has been designed to estimate maximum rail to ground voltage in train networks with DC Power Distribution. There are two methods by which this estimate can be made. These methods are termed the Old Method and the New Method. The terms are applied to versions of the model lower than 3.5 (Old Method) and 3.5 and higher (New Method). Both methods can be used with version 3.5 and higher.

Old Method
This method can estimate maximum rail to ground voltage in very simple two track networks and with a single train running on the network.

Rail voltage estimates can be made on more complicated networks by separating them into pieces, where each piece is a simple network described above.

New Method
This method can estimate maximum rail to ground voltage in any train network with no limits on the number of trains running. It utilizes the return circuit to make the estimate and depends on the line currents moving through the rails.

This manual has a companion EXCEL Book:

TOMInstructionManualExercisingTheRailVoltageModel.xls

in which many of the results of this exercise are tabulated. The reader will be referred there via hyperlink for those cases. There is an Index in this EXCEL Book. The book is always open to the index, from which the reader can choose his destination.

For example, clicking the entry TOMInstructionManualExercisingTheRailVoltageModel.xls [Index of Sheets], will take the reader to the EXCEL Book index. He then clicks the Index of Sheets entry in the workbook to get to the desired entry.

Section 2 outlines the procedure for both the Old and New Method for applying the Rail Voltage Model (RVM).

Section 3 describes the application of the new procedure to a simple DC Rail System for both no regeneration and regeneration cases. Several of its features are described and parameter variation on many fronts is studied.
Section 4 shows the application to a more complicated DC system, which is an extension of the DCEE Instruction Manual.
2 RAIL VOLTAGE MODEL PROCEDURE

The RVM Old Method and New Method screen procedure mechanics are described in the Program Manual for both the Input and RVM Running.

Several steps are required in order to determine rail voltage. Most (1-6) of these steps have been carried out in Volume 10 – Instruction Manual for Including the Return Circuit in Electric Rail Systems. These steps will not be repeated in this manual. Links are provided in the steps themselves.

1. Build the Return Circuit in accordance with the Return Circuit Rail Voltage requirements. See Volume 10.
4. Build the ENS or TMS File of Filenames, which contains the Network file just built. See Volume 10.
5. Run the ENS or TMS.
6. Run the FMM Current Analysis program to obtain the Return Circuit Current Analysis Output file using the Current Measurement Output file from the ENS or TMS run.
8. Build a matching Rail Voltage Table.
9. Build a RVM File of Filenames file using as input the Return Circuit Rail Voltage file, the Rail Voltage Table file and the Return Circuit Current Analysis Output file.
10. Run the RVM.
11. Presentation of RVM Output.

Even though Step 6 was demonstrated in Volume 10 – Instruction Manual for Including the Return Circuit in Electric Rail Systems, it is repeated here because of the changes in the screens from earlier versions of the model to Version 3.5.

2.1 FMM CURRENT ANALYSIS PROGRAM

Assuming that steps 1 to 5 were carried out, the FMM Current Analysis Program is now demonstrated as step 6 in the Rail Voltage Model procedure.

Begin with the FMM Main screen with the TEST transit system selected.
Click the **Current Analyzer** command button.
Select the **AO-4n.tes Current Measurement Output** file.
Click the **Choose Circuit** combo box and select the **Return Circuit** file RC-4n.tes.
Click the Create File command button to run the Current Analyzer. The result will be the Return Circuit Current Analysis Output file, RCA4n.tes.

2.2 RETURN CIRCUIT RAIL VOLTAGE FILE

Open the FCM Main screen, choose the TEST rail system and click the RVM Input checkbox.
Select the **Rtn Cct RV** item in the **RVM Input** list box to obtain the next screen.
Select the **RC-4.tes Return Circuit** file.

Click the **Resistances** command button to obtain the **Resistance Procedure** screen.
This screen allows the user to choose the **Ground Resistance** and **Rail to Ground Leakage Resistance**, which will be input to the grids of the previous screen. This is the general values, which will be used everywhere in the circuit. Later, the user is given an opportunity to change the values in specific lines of the circuit in the graphical procedure.

Click the **Set Resistance To Grid** command button and proceed to the previous screen.
Click the **Graphic Input** command button to obtain the next screen.

Click the **Open Grid** command button to display the circuit.
The resistances currently associated with any line can be changed. Click on the line with the right mouse button.
Choose the **Set Resistances** menu item to produce the next screen.

Enter the specific resistances associated with line B0, if they are different than the general resistances. Click the **Set Resistances To Grid** command button to insert the new resistances into the grids.
Nodes are normally floating. Any node may be grounded by the following procedure. Click with the right mouse button on the node.
Click the **Ground** menu item to ground the node **B3**. Exercise the procedure again to unground the node.

Return to the **Main** screen to complete the process.

Click the **Create File** command button.
Click Yes if a line translation is wanted and No if not. A line translation translates the TOM line name assignment to a more recognizable one as illustrated.
2.3 **RAIL VOLTAGE TABLE**

Once the **Return Circuit Rail Voltage** file has been built, a **Rail Voltage Table** file, more in line with the **Return Circuit Rail Voltage** file can be built.

On the **FCM – Main Screen**, select the **RV Table** item in the **RVM Input** list box.

![Rail Voltage Table](image)

Click the Choose Return Circuit RV File combo box and select the Return Circuit RV file RX-4.tes, just created.
The parameters fitting the particular **Return Circuit RV** file are set up automatically. Click the Create File command button to complete the process, which may be viewed next.
2.4 **RVM FILE OF FILENAMES**

Creating the RVM File of Filenames is similar to the creation of any of the simulator’s file of filenames.

On the **FCM – Main Screen**, select the Fnames item in the **RVM Input** list box.
Completion of the screen yield the next screen.
The file is then created.

### 2.5 RVM OPERATION
All of the input files were built, so now the RVM may be called.

Begin with the TOM main screen.
Click the **Rail Voltage Model** command button, and select the TEST rail system.
Select the **RVM File of Filenames RVM4n.tes**.

Review the output.
2.6 Presentation of RVM Output

RVM Output is presented by constructing output tables in EXCEL and by providing plots of Rail Voltage Profiles, which are either position-based or time-based.

2.6.1 Maximum Rail Voltage Output Tables in EXCEL

By clicking the EXCEL Ready command button in the previous screen containing a display of the Rail Voltage Detailed Output file, the next screen is presented.
The user is informed that the Clipboard will hold the EXCEL table information. After the OK command button is clicked, the information

```
RVD4n.tes DC Test Pri wo Ties Rtn wo Bonds NReg 6 Cars  53.4  1  1  8:28:00  A3
```

is on the Clipboard. It is in EXCEL format, so that it may be pasted into an EXCEL Spreadsheet.

An example of such a table is shown next.

```
<table>
<thead>
<tr>
<th>Output File</th>
<th>Condition</th>
<th>Maximum Rail Voltage Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVD4n.tes</td>
<td>DC Test Pri wo Ties Rtn wo Bonds NReg 6 Cars</td>
<td>Voltage: 53.4  Position: 1.00  Track Number: 1  Snapshot: 8:28:00  Node Name: A3</td>
</tr>
<tr>
<td>RVD4n.tes</td>
<td>DC Test Pri wo Ties Rtn wo Bonds NReg 5 cars</td>
<td>Voltage: 53.4  Position: 1.00  Track Number: 1  Snapshot: 8:28:00  Node Name: A3</td>
</tr>
<tr>
<td>RVD4n.tes</td>
<td>DC Test Pri wo Ties Rtn wo Bonds NReg 6 cars</td>
<td>Voltage: 53.4  Position: 1.00  Track Number: 1  Snapshot: 8:28:00  Node Name: A3</td>
</tr>
</tbody>
</table>
```

The paste is effected by placing the focus on the white cell and pressing the <ctrl> V Key.
2.6.2 Rail Voltage Profiles

Rail Voltage Profiles may be position based or time based. Each of these are discussed separately.

A Position Based Rail Voltage Profile is a map over a fixed track at a fixed time of the Rail Voltage.

A Time Based Rail Voltage Profile is a display over time for a fixed track and fixed position of the Rail Voltage.

Begin with the Graphics Utility – Main Screen with the TEST rail system selected.

Select the Electrical Graphs checkbox.
Click the **DC Trains** checkbox.

Click the **Rail Voltage Position / Time** checkbox.
Select a **RVM Detailed Output** file and a **Station** file, preferably one containing the location of substations.
If it is desired to place a scale on the x and y-axes of the resulting graph, first graph without a scale to determine limits and step size, then set the scale. The following scale will be set using the limits, which have already been determined. Click the Set Scale checkbox and fill in those limits and step size.

Return to the previous screen.
There are three checkboxes in the Rail Voltage Graphs frame. These are

- Maximum Rail Voltage vs Position
- Rail Voltage vs Position
- Rail Voltage vs Time

In addition the conditions for the global Maximum Rail Voltage are displayed in the frame for reference.

- Time of Occurrence (Snapshot)
- Position of Occurrence
- Track Number of Occurrence
- Absolute Value of Maximum Rail Voltage
- Node Name of Occurrence

The Maximum Rail Voltage vs Position is the Maximum Rail Voltage at each Snapshot irrespective of its Position or Track Number.

The Rail Voltage vs Position is the Position Based Rail Voltage Profile.

The Rail Voltage vs Time is the Time Based Rail Voltage Profile.

Click the Complete Graph command button to produce the plot.

The Global Maximum Rail Voltage occurs at Substation 2. Local Maximum Rail Voltages, which show up between substations, occur at trains.
Before discussion of the **Position Based** and **Time Based Rail Voltage Profiles**, it is necessary to allow negative values in the plots to represent values of voltages below the ground.

### 2.6.2.1 Position Based Rail Voltage Profile

Click the **Rail Voltage vs Position** checkbox in the **Rail Voltage Graphs** frame.
The conditions in the frame are those of the **Global Maximum Rail Voltage**. The **Position Increment** text box default is set at 0.01 (miles or kilometers), which means the points in the plot will be displayed every 0.01 units of distance along the **Track Number** and **Snapshot** shown.

Any **Track Number** or **Snapshot** can be selected for the graph.

Click the **Complete Graph** command button to display the plot.
2.6.2.2 Time Based Rail Voltage Profile

In the Rail Voltage Graphics frame, click the Rail Voltage vs Time checkbox.
The **Position** and **Track Number** of the **Global Maximum Rail Voltage** is displayed in the text box and combo box, respectively. Any **Position** or **Track Number** could be selected.

Click the **Complete Graph** command button to display the plot.

The time of the **Global Maximum Rail Voltage** is seen and it has a negative value in this case.

This completes the mechanics of the **RVM**. The next section begins application to the **DC TEST Rail System**.

### 3 APPLICATION TO TEST DC RAIL SYSTEM

For this purpose, a simple DC Rail System was used as the basis for illustrating the methods and their comparison. Concentration was on the power distribution system (**ENS** - related) aspects, rather than the **TPS** aspects.

The **DC TEST Rail System** consisted of a two-track line between end of track positions 0.1 and 3.1, which was fed by four substations, at positions 0, 1, 2, 3. Both no regeneration and regeneration capability was included in the trains. The system is described further in the **Volume 10 Instruction Manual**.
3.1 CIRCUITS USED IN APPLICATION

Three basic circuits will be used in applying the RVM to the DC TEST system. These circuits include one primary circuit and two return circuits. These are fully described in the Volume 10 Instruction Manual.
3.1.1 **Primary Circuit Without Ties**

The Primary Circuit Without Ties sketch is shown next.

The circuit file name is **PC-4.tes** and a graphic picture of it is shown next.
3.1.2 **Return Circuit Without Bonds**

The **Return Circuit Without Bonds** sketch is shown next.
The circuit file name is **RC-4.tes** and a graphic picture of it is shown next.
3.1.3 Return Circuit With Bonds

The Return Circuit With Bonds sketch is shown next.
The circuit file name is **RC-4b.tes** and a graphic picture of it is shown next.
3.2 PARAMETER STUDY

The RVM results depend on ground resistance, rail to ground leakage resistance and the current in the rails. This quick study considers variation of maximum rail to ground voltage as these parameters vary.

3.2.1 Resistances

The variation of maximum rail voltage with variation of the ground resistance and rail to ground leakage resistance was undertaken. This variation was considered for both return circuits with and without bonds. The cases of regeneration and no regeneration were also included.
3.2.1.1 Return Circuit Without Bonds

The next graph shows the variation of Rail Voltage with the ratio of Leakage to Ground Resistances for the case without rail bonds.

![Graph showing Rail Voltage (No Bonds) vs. Ratio Leakage to Ground Resistances]

Within the range of the study on the DC Test system on the non-bonded circuit (bonds only at substations and ends of track), the maximum rail voltage varied approximately with the ratio of Rail to Ground Leakage Resistance / Ground Resistance Per Mile, as displayed in the graph. This was the case for both regeneration and no regeneration.

In the case of regeneration, the rail voltages were higher for higher values of the ration of leakage to ground but gradually became closer to the no regeneration case as this ratio decreased.

In order to obtain a better feel for the circumstances, the following drawing is present for a Ground Resistance of 25 Ω/mile and a Leakage Resistance of 1000 Ω, a ratio of 500 with no regeneration.
The above drawing shows the rail current in the top part of the picture and the nodal and lineal rail voltage in the bottom half. Since the rail voltage varies linearly between the nodes, the voltage at the nodes determines the voltage profile of the rail at any point between the nodes.

Caution is appropriate here since both ground and rail to ground leakage resistances can vary over large ranges even on the same rail transit system.

Another important parameter in the rail voltage calculation is rail current. Variation of rail current is presented in the Section 3.2.2.
3.2.1.2 Return Circuit With Bonds

The next graph shows the variation of Rail Voltage with the ratio of Leakage to Ground Resistances for the case with rail bonds.

Within the range of the study on the DC Test system on the bonded circuit (bonds at substations, ends of track and every 0.25 miles), the maximum rail voltage varied approximately with the ratio of Rail to Ground Leakage Resistance / Ground Resistance Per Mile, as displayed in the graph. This was the case for both regeneration and no regeneration.

It is quite clear that for the same resistance parameters, the rail voltage is much smaller in the bonded case as opposed to the unbonded. Because adding rail bonds improves the conductivity of the circuit, peak currents are reduced and the value of minimum voltage is increased.

In the case of both regeneration and no regeneration, the maximum rail voltage over the range of resistance ratios changed positions from rail bond to train to substation. To view these changes, please see the companion EXCEL book

TOMInstructionManualExercizingTheRailVoltageModel.xls
Click the **Resistance Study Table** on the index page. For convenience, the table is displayed next.

### 3.2.1.3 Resistance Study Parameter/Results Table

The table showing the range of parameters and results in the resistance study is shown next.

<table>
<thead>
<tr>
<th>Resistance Parameters</th>
<th>Return Circuit Without Bonds</th>
<th>Return Circuit With Bonds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage</td>
<td>Ground</td>
<td>Ratio L/G</td>
</tr>
<tr>
<td>400</td>
<td>0.1</td>
<td>2000</td>
</tr>
<tr>
<td>250</td>
<td>0.5</td>
<td>2000</td>
</tr>
<tr>
<td>250</td>
<td>1</td>
<td>2000</td>
</tr>
<tr>
<td>250</td>
<td>2</td>
<td>2000</td>
</tr>
<tr>
<td>250</td>
<td>5</td>
<td>2000</td>
</tr>
<tr>
<td>250</td>
<td>10</td>
<td>2000</td>
</tr>
<tr>
<td>250</td>
<td>25</td>
<td>2000</td>
</tr>
<tr>
<td>500</td>
<td>1</td>
<td>2000</td>
</tr>
<tr>
<td>500</td>
<td>2</td>
<td>2000</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
<td>2000</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>2000</td>
</tr>
<tr>
<td>500</td>
<td>25</td>
<td>2000</td>
</tr>
</tbody>
</table>

### 3.2.2 Rail Current Variation

**Rail Voltage** is proportional to **Rail Current**, but not in a direct way. Higher rail currents imply higher rail voltages and larger voltage drops (poorer voltage regulation) on the rail system.

Two methods to obtain larger (smaller) rail currents are increasing (decreasing) the number of cars per train and/or decreasing (increasing) the headway on the system. Each of these methods is considered.
3.2.2.1 Increasing (Decreasing) Number of Cars per Train

In order to determine the rail voltage by increasing the number of cars, the following steps are taken.

- Build new **Train** files with the increased number of cars per train for both regeneration and no regeneration (2 files).
- Build new **TPS Files of Filenames** with the new trains on the same right of way (4 files).
- Run the **TPS** using the **TPS File of Filenames** files (4 runs).
- Build new **ENS Files of Filenames** with new **Power Profiles** output from the new **TPS** runs (2 files).
- Run the **ENS** using the **ENS File of Filenames** files (2 runs).
- Using the **FMM**, run the **Current Analyzer** program using the **Current Measurement Output** files from the new **ENS** runs (2 files).
- Build new **RVM Files of Filenames** files with new **Current Analysis Output** files from the new **Current Analyzer program** runs (2 files).
- Run the **RVM** using the **RVM File of Filenames** files just built and obtain the **Rail Voltage Detailed Output** files.
- Presentation of **RVM Output** by comparing the maximum rail voltages of the trains with increased number of cars to the ones with the normal number of cars.

Samples of each of the steps will be shown in the next sections.

3.2.2.1.1 Train Files

This is done first by going to the **FCM – Main Screen**, clicking the **TPS Input** checkbox, selecting the **Train** item, importing the base **Train** file **T-Cb.tes** and clicking the **Train Makeup Input** checkbox to obtain the **Train Makeup Input** screen, shown next.
Change the \# Cars Type 2 entry from 5 to 8.
The number of cars per train is now 9, rather than the previous 5. Click the Select command button to return to the **Train File Input – Main Screen** and select the filename for the new file and then create the file.
The file for the case of regeneration is modified in the same manner.

### 3.2.2.1.2 TPS File of Filename Files

This is done first by going to the FCM – **Main Screen**, clicking the TPS Input checkbox, selecting the Fnames item and importing the base File of Filenames file TPSdc+.tes shown next.
The following entries are changed.

- T-Ch.tes to T-Chi.tes
- TPSdc+.tes to TPSdc+.tes
- P-dc+.tes to P-dc+.tes
- TSSdc+.tes to TSSdc+.tes
- Caption 6 cars to 9 cars

The file is created as well as the remaining 7 files.

### 3.2.2.1.3 TPS Runs

The **TPS** may now be batched to cover the increased cars per train runs.

Click the **TPS** on the main screen and select the **TEST** system.
Holding down the <ctrl> key, click on the File of Filenames files, which are to be batched. Equivalently, place the mouse down on the first file to be batched and drag the mouse to the last file to be batched.
Click the Select command button under the selected files. This action will cause the execution of these files in succession.

### 3.2.2.1.4 ENS File of Filenames

Two ENS File of Filenames must be built to accommodate the runs with 9 cars per train.

Begin with the ENS File of Filenames Input screen to which the ENS File of Filenames for the 6 cars per train is imported.
Make the following changes.

Remove the **Power Profiles** in the **Input File Name** list box. These are **P-dc+.tes** and **P-dc-.tes**. These are removed by double clicking on them.

Then, click on the **Power Profile Inputs** entry in the **Input File Type** list box.
Select the files \texttt{P-dci-.tes} and \texttt{P-dci+.tes}, by double clicking on them and then change the ENS File of Filenames from \texttt{ENS4n.tes} to \texttt{ENS4ni.tes}, the Current Measure Output filename from \texttt{AO-4n.tes} to \texttt{AO-4ni.tes} and the 6 cars to 9 cars in the File Caption. The completed screen is shown next.
Create the file and then create the file in the same manner for the regeneration case, which will be named ENS4ri.tes.

3.2.2.1.5 ENS Runs

The setup is shown in the next screen.
Click the Select command button under the selected files to execute the runs in succession.

3.2.2.1.6 Current Analysis

The Current Measurement Output files produced by the ENS are now current analyzed. On the FMM - Main Screen, select the TEST rail system and click the Current Analyzer command button to produce the next screen.
Select the **Current Measurement Output** file `AO-4ni.tes` to produce the next screen.
Click the Choose Circuit combo box and select the Return Circuit file RC-4.tes.
Click the **Create File** command button to analyze the circuit currents. This action will produce the following **Return Circuit Current Analysis Output** file as shown in the next screen.
The **RMS Currents** can be viewed immediately by clicking the View RMS Currents command button.

This file is used as input to the **RVM**. The same procedure is now carried out for the regeneration case (**RCA4ri.tes**).
3.2.2.1.7  **RVM File of Filenames Files**

Two **RVM File of Filenames** file are now built using the results produced in the previous section; one for the no regeneration case and one for the regeneration case. The next steps show the building for the regeneration case.

On the **FCM Main Screen** select the **TEST** rail system and **RVM Input** to produce the next screen.

Select the **Fnames** item in the **RVM Input** list box.
Select the RVM File of Filenames file RVM4r.tes to produce the next screen.
Select the **Cur Analysis Output File** item in the **Input File Type** list box to produce the next screen.
Modify the screen as follows.

- Select RCA4ri.tes from the List of Files.
- Change the Fnames input file from RVM4r.tes to RVM4ri.tes.
- Modify the names of the output files from 4r to 4ri.
- Create the file.
The same procedure is now applied to the no regeneration case.

3.2.2.1.8 **RVM Runs**

On the **TOM Main Screen**, click the **Rail Voltage Model** command button and select the **TEST** rail system.
Select the **RVM File of Filenames** file **RVM4ni.tes**.

The result is the next screen.
Click the Yes command button to review the results.
The procedure is now repeated for the case of no regeneration.

### Rail Voltage Comparisons

Rail voltage comparison is achieved by comparing maximum rail voltages between the six car train runs and the nine car train runs for both regeneration and no regeneration cases.

Secondly, the rail voltage profile for the case of maximum voltage is also compared.

#### Maximum Rail Voltage Comparison

The maximum rail voltage can be compared between the 6-Car and 9-Car cases for both no regeneration and regeneration. The next table shows the comparison.
Note that A3 is the node representing the substation connection at Position 1.000 on Track 1 and B3 is the node representing the substation connection at Position 1.000 on Track 2. Trp 1 and Trp 2 are the trains R1E1 on Track 1 and R1W1 on Track 2.

It is clear in this case that rail voltages have increased as the load on the line gets larger (6-Car ➔ 9-Car). Regeneration produces rail voltages in this case which are slightly higher.
3.2.2.1.9.2 Rail Voltage Profiles

The graphics package allows the display of Rail Voltage Profiles, where 6-Car and 9-Car trains are used.

No Regeneration

Maxima occur at the same position and same snapshot but on different tracks.

No discussions will occur here on Rail Voltage Profile comparisons since this manual is for the purpose of instruction in the tools.
Regeneration
3.2.2.2 Decreasing (Increasing) Train Headway

In order to determine the rail voltage by decreasing the headway from 5 minutes to 2.5 minutes, the following steps are taken.

- Build a new **Train Location** file with a headway of 2.5 minutes. (1 file)
- Build a new **Operating Time** file which represents 2.5 minutes of run time. (1 file)
- Build a new **ENS File of Filenames** file with the new files just built so that the trains run every 2.5 minutes. (2 files).
- Run the **ENS** using the **ENS File of Filenames** files (2 runs).
- Using the **FMM**, run the **Current Analyzer** program using the **Current Measurement Output** files from the new **ENS** runs (2 files).
- Build new **RVM Files of Filenames** files with new **Current Analysis Output** files from the new **Current Analyzer** program runs (2 files).
- Run the **RVM** using the **RVM File of Filenames** files just built and obtain the **Rail Voltage Detailed Output** files.
- Compare the maximum rail voltages of the trains with increased number of cars to the ones with the normal number of cars.

As in the previous section, minimal screens will be displayed to complete the steps.

3.2.2.2.1 **Train Location File**

Proceed to the **FCM – Train Location File Input** screen. On the **FCM – Main Screen**, select the **TEST** rail system, the **ENS Input** checkbox and the **Trn Loc** item in the **ENS Input** list box.
Click the **Headway** checkbox to produce the next screen.
The completed screen is shown next.
Create the file and review the timetable just built.
3.2.2.2 Operating Time File

Proceed to the FCM – Operating Time File Input main screen. On the FCM – Main Screen, select the TEST rail system, the ENS Input checkbox and the Op Time item in the ENS Input list box.
The completed screen is next.
3.2.2.2.3 **ENS File of Filenames**

Two **ENS File of Filenames** files must be built to accommodate the runs with 2.5 minute headways.

The procedure is the same as in Section 3.2.2.1.4 except for the following file name changes:

- **Train Location** file TL-dch.tes replaces TL-dc.tes.
- **Operating Time** file OP-dch.tes replaces Op-dc.tes.
- **ENS File of Filenames** file ENS4nh.tes replaces ENS4n.tes.
- **Current Measurement Output** file AO-4nh.tes replaces AO-4n.tes.

In the files for regeneration r replaces n.

3.2.2.2.4 **ENS Runs**

The **ENS** runs are the same as in Section 3.2.2.1.5 except that the filenames are ENS4nh.tes and ENS4rh.tes.

3.2.2.2.5 **Current Analysis**

Current analysis is performed the same as in Section 3.2.2.1.6 except that the **Current Measurement Output** files are AO-4nh.tes and AO-4rh.tes and the resulting **Current Analysis Output** files are RCA4nh.tes and RCA4rh.tes.

3.2.2.2.6 **RVM File of Filenames Files**

The **RVM File of Filenames** is built using the procedure of Section 3.2.2.1.7. The **Current Analysis Output** files are now RCA4nh.tes and RCA4rh.tes. The **RVM File of Filenames** and associated **Summary** and **Detailed Output** files are named with the h replacing the i.

3.2.2.2.7 **RVM Runs**

The **RVM** runs are made in the same way as Section 3.2.2.1.8 except the **RVM File of Filenames** files are RVM4nh.tes and RVM4rh.tes.
3.2.2.2.8 Rail Voltage Comparisons (Current Related)

Rail voltage comparison is achieved by comparing maximum rail voltages between 5 minute headway and 2.5 minute headway runs for both regeneration and no regeneration cases. The line current will be different in magnitude and distribution. The magnitude effect is small.

Secondly, the rail voltage profile for the case of maximum voltage is also compared.

3.2.2.2.8.1 Maximum Rail Voltage Comparison

The maximum rail voltage can be compared between the 2.5 and 5 minute headway cases for both no regeneration and regeneration. The next table shows the comparison.

<table>
<thead>
<tr>
<th>Maximum Rail Voltage</th>
<th>5-Minute Headway</th>
<th>2.5 Min Headway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>53.4</td>
<td>55.6</td>
</tr>
<tr>
<td>Position</td>
<td>1.000</td>
<td>1.600</td>
</tr>
<tr>
<td>Track Number</td>
<td>1.000</td>
<td>1.600</td>
</tr>
<tr>
<td>Node Name</td>
<td>A3</td>
<td>A3</td>
</tr>
<tr>
<td>Snapshot</td>
<td>8:22:90.0</td>
<td>8:23:40.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Peak Current</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>8668.1</td>
<td>8718.3</td>
</tr>
<tr>
<td>Position</td>
<td>0.453</td>
<td>1.617</td>
</tr>
<tr>
<td>Track Number</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Trains</td>
<td>R1E1</td>
<td>R1W1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minimum Voltage</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>608</td>
<td>593.7</td>
</tr>
<tr>
<td>Position</td>
<td>1.636</td>
<td>1.565</td>
</tr>
<tr>
<td>Track Number</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Trains</td>
<td>R1W1</td>
<td>R1W1</td>
</tr>
</tbody>
</table>

In this case, the peak currents for 2.5 minute headway running are only slightly larger than the 5-minute headway running case resulting in very little increase in maximum rail voltage.
3.2.2.8.2 Rail Voltage Profiles

No Regeneration

![Graph showing rail voltage profiles for different sections.

Max Voltage: 26.9 V
Min Voltage: 5.3 V
Snapshot Time: 6:29:09
Track 1

- Section 0
- Section 1
- Section 2
- Section 3
- Section 4

Voltage variations at different positions.

Voltage peaks at positions 2.5 min hw, 5 min hw, 2.5 min hw, 5 min hw.
Regeneration

3.2.3 Influence of Rail Bonds
Rail bonds improves the conductivity of the circuit, reducing peak line currents and increasing the value of minimum voltage. Two cases are considered. A diagram of the bonded circuit is shown next.
The rail bonds are 0.25 mi apart. The procedure for obtaining rail voltage was specified in Section 2.
### 3.2.3.1 Maximum Rail Voltage Comparisons

Maximum rail voltages are compared between the bonded circuit and the circuit with no bonds for no regeneration and regeneration.

The results are presented in the table.

<table>
<thead>
<tr>
<th>Rail Voltage Results - Rail Bonds</th>
<th>No Bonds</th>
<th></th>
<th>Bonds</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Rail Voltage</td>
<td>No Regeneration</td>
<td>Regeneration</td>
<td>No Regeneration</td>
<td>Regeneration</td>
</tr>
<tr>
<td>Valua</td>
<td>53.4</td>
<td>56.6</td>
<td>37.4</td>
<td>44.6</td>
</tr>
<tr>
<td>Position</td>
<td>1.000</td>
<td>1.000</td>
<td>1.760</td>
<td>1.769</td>
</tr>
<tr>
<td>Track Number</td>
<td>1.000</td>
<td>1.000</td>
<td>1.760</td>
<td>1.769</td>
</tr>
<tr>
<td>Node Name</td>
<td>A3</td>
<td>A3</td>
<td>A3</td>
<td>A3</td>
</tr>
<tr>
<td>Snapshot</td>
<td>8.228.00</td>
<td>8.234.00</td>
<td>8.233.00</td>
<td>8.233.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Peak Current</th>
<th>Valua</th>
<th>Position</th>
<th>Track Number</th>
<th>Train</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8668.1</td>
<td>8718.3</td>
<td>8322.1</td>
<td>8361.6</td>
</tr>
<tr>
<td></td>
<td>0.453</td>
<td>1.617</td>
<td>1.617</td>
<td>1.617</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>R101</td>
<td>R101</td>
<td>R101</td>
<td>R101</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minimum Voltage</th>
<th>Valua</th>
<th>Position</th>
<th>Track Number</th>
<th>Train</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>608</td>
<td>593.7</td>
<td>632.6</td>
<td>622.9</td>
</tr>
<tr>
<td></td>
<td>1.635</td>
<td>1.655</td>
<td>1.636</td>
<td>1.655</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>R101</td>
<td>R101</td>
<td>R101</td>
<td>R101</td>
</tr>
</tbody>
</table>

### 3.2.3.2 Rail Voltage Profiles

The rail voltage profiles for the maximum rail voltage snapshot and track number are shown next.
3.2.4 Grounded Circuit

The Rail Voltage Model Procedure, outlined in Section 2, allows for grounding circuits. Normally, a DC Rail System is not grounded, but may deliberately or accidentally get grounded. This means an extremely low leakage resistance from rail to ground at some point in the return circuit.

A circuit could be grounded at an existing node or somewhere on any line. Since the grounding procedure for somewhere on a line actually means adding another node and then grounding that node, demonstration of grounding a line is more comprehensive, and includes the demonstration of grounding a node. The single ground on an existing line is now demonstrated in some detail.

3.2.4.1 Single Ground

Begin with the Return Circuit Without Bonds, illustrated in Section 3.1.2. The TOM graphic image of this circuit (file: RC-4.tes) is shown there and below.

Suppose a ground occurs at Position 1.2 on Track 1. The first step is to place a node at this position.
Now save this new return circuit in the file RC-4g.tes.

Steps 2-6 of the Rail Voltage Model Procedure of Section 2 are now carried out. The files generated by these steps will be:

1. Return Circuit file: RC-4g.tes
2. Return Circuit Impedance file: ZR-4g.tes
3. Network file: N-4g.tes [Combines Primary Circuit file: PC-4.tes with RC-4g.tes and ZR-4g.tes]
4. ENS File of Filenames file: No Regeneration ENS4gn.tes, Regeneration ENS4gr.tes
6. Current Analysis Output file: No Regeneration RCAgn.tes, Regeneration RCA4gr.tes

Step 7, building the Return Circuit Rail Voltage file, is demonstrated here.

Begin with the FCM – Return Circuit Rail Voltage File Input – Return Circuit for Rail Voltage by Graphics screen, shown next.
The method to get to this screen is demonstrated in Section 2.2 and will not be repeated here.

Right click on the node, which was just added at Position 1.2 on Track 2.
Click the **Ground** item of the pop-up menu. This action will ground the circuit at this point.

Click the **Close** command button.

Add the resistances in the usual manner (See Section 2.2) and create the file: **RX-4g.tes**.
Steps 8-10 of the **Rail Voltage Model Procedure** of Section 2 are now conducted.

The results are presented in the usual two parts, maximum rail voltage and rail voltage profiles.

### 3.2.4.1.1 Maximum Rail Voltage Comparisons

Maximum rail voltages are compared between the ungrounded and grounded circuits for no regeneration and regeneration.

The results are presented in the table.

<table>
<thead>
<tr>
<th>Rail Voltage Results - Ground (Trk 1 Pos 1.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Rail Voltage</strong></td>
</tr>
<tr>
<td>Value</td>
</tr>
<tr>
<td>Position</td>
</tr>
<tr>
<td>Track Number</td>
</tr>
<tr>
<td>Node Name</td>
</tr>
<tr>
<td>Snapshot</td>
</tr>
<tr>
<td><strong>Peak Current</strong></td>
</tr>
<tr>
<td>Value</td>
</tr>
<tr>
<td>Position</td>
</tr>
<tr>
<td>Track Number</td>
</tr>
<tr>
<td>Train</td>
</tr>
<tr>
<td><strong>Minimum Voltage</strong></td>
</tr>
<tr>
<td>Value</td>
</tr>
<tr>
<td>Position</td>
</tr>
<tr>
<td>Track Number</td>
</tr>
<tr>
<td>Train</td>
</tr>
</tbody>
</table>
3.2.4.1.2 Rail Voltage Profiles

The rail voltage profiles for the maximum rail voltage snapshot and track number are shown next.

No Regeneration

In this case, the maximum rail voltage occurs on track 2 but the profile of track 1 is shown because of the ground location.
Regeneration

![Graph showing rail voltage with and without regeneration](image-url)
3.2.4.2 Double Ground
In addition to the ground on Track 1 at Position 1.2, a second ground is placed on Track 1 at Position 1.8. The procedure is the same as illustrated in the previous Section 3.2.4.1.

3.2.4.2.1 Maximum Rail Voltage Comparisons
Maximum rail voltages are compared between the ungrounded and grounded circuits for no regeneration and regeneration.

The results are presented in the table.

<table>
<thead>
<tr>
<th>Rail Voltage Results - Ground (Trk 1 Pos 1.2 &amp; 1.8)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Rail Voltage</strong></td>
</tr>
<tr>
<td>Value</td>
</tr>
<tr>
<td>Position</td>
</tr>
<tr>
<td>Track Number</td>
</tr>
<tr>
<td>Node Name</td>
</tr>
<tr>
<td>Snapshot</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Peak Current</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Value</strong></td>
</tr>
<tr>
<td>Position</td>
</tr>
<tr>
<td>Track Number</td>
</tr>
<tr>
<td>Train</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minimum Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Value</strong></td>
</tr>
<tr>
<td>Position</td>
</tr>
<tr>
<td>Track Number</td>
</tr>
<tr>
<td>Train</td>
</tr>
</tbody>
</table>
3.2.4.2.2 Rail Voltage Profiles

The rail voltage profiles for the maximum rail voltage snapshot and track number are shown next.

No Regeneration

![Rail Voltage Profile Diagram]
Regeneration

3.2.5 Low Ground Resistance in Area

Normally, ground resistance is set for the rail system even though both the ground resistance and rail to ground leakage resistance varies over the whole area. The leakage and ground resistance considered in these previous examples were pretty conservative and most likely would appear in new rail systems. These values were

- Rail to Ground Leakage 1000 Ω.
- Ground Resistance 25 Ω/mile.

On wet days, with the ground contaminated and/or buried pipe running parallel to the rail, the ground resistance may get very low. It is assumed for the purpose of this exercise, that the ground resistance around Substation 1 (Position 1 on Track 1) is 2Ω/mile and the leakage resistance remains the same. To be more specific, the area on Track 1 between mileposts 1.000 and 1.200 has a ground resistance of 2Ω/mile.

Begin with the grounded circuit, importing the Return Circuit for Rail Voltage file, RX-4g.tes into the FCM – Return Circuit Rail Voltage – Main Screen as shown next.
Click the **Graphic Input** command button and open the graphics screen.

The first task is to “unground” the node at **Position 1.2** on **Track 1**.
Right click on the node to produce the next screen.

![Image of circuit layout]

Click the **UnGround** menu item.

![Image of information message]

The next task is to set the ground resistance of the track between Position 1 and 1.2 to 2Ω/mile.
Right click on the line to produce the next screen.

Click the **Set Resistances** menu item to obtain the next screen.
Set the **Ground Resistance** to 2.

Click the **Set Resistances To Grid** command button to obtain the next screen.
Note that $2\Omega/\text{mile} \times 0.2\text{ miles} = 0.4\ \Omega$.

Click the OK command button to return to the Graphics screen.
Right click on the track again.

Select the **Identify** menu item.
Return to the main screen by closing the **Graphics** screen. Modify **File Caption** and **File Name** as shown.

Create the file.
The remaining items in the procedure are

- Build a matching **Rail Voltage Table**.
- Build a **RVM File of Filenames** file using as input the **Return Circuit Rail Voltage** file, the **Rail Voltage Table** file and the **Return Circuit Current Analysis Output** file.
- Run the **RVM**.

These steps will not be repeated here.

### 3.2.5.1.1 Maximum Rail Voltage Comparisons

Maximum rail voltages are compared between the low ground resistance and ungrounded circuits for no regeneration and regeneration.

The results are presented in the table.

| Rail Voltage Results - Low Ground Resistance Pos 1.0 - 1.2 Track 1 |
|------------------------|-------------------|-------------------|-------------------|-------------------|
| **Maximum Rail Voltage** | Normal Resistance | Low Resistance |
| Value | 53.4 | 55.6 | 53.6 | 55.7 |
| Position | 1.000 | 1.000 | 1.000 | 1.000 |
| Track Number | 1 | 1 | 2 | 2 |
| Node Name | A3 | A3 | B3 | B3 |
| Snapshot | 8: 2:28.00 | 8: 2:34.00 | 8: 2:28.00 | 8: 2:34.00 |

<table>
<thead>
<tr>
<th>Peak Current</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Value</strong></td>
</tr>
<tr>
<td><strong>Position</strong></td>
</tr>
<tr>
<td>Track Number</td>
</tr>
<tr>
<td>Train</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minimum Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Value</strong></td>
</tr>
<tr>
<td><strong>Position</strong></td>
</tr>
<tr>
<td>Track Number</td>
</tr>
<tr>
<td>Train</td>
</tr>
</tbody>
</table>
3.2.5.1.2 **Rail Voltage Profiles**

The rail voltage profiles for the maximum rail voltage snapshot and track number are shown next.

**No Regeneration**
Regeneration

![Diagram showing RAIL VOLTAGE with various voltage levels at different positions on the track. The diagram includes labels for 'Low Grd Res', 'Normal Grd Res', and 'Snapshot Time: 6:23:400 Track 1'.]
4 APPLICATION TO DCEE

4.1 DESCRIPTION OF THE DCEE RAIL SYSTEM

The DCEE Rail System to be used for this work is described in Volume 10 – Instruction Manual for Including the Return Circuit in Electric Rail Systems.

This description will not be repeated here, except to say that files related to the AM Peak operation were considered for rail voltage analysis.

4.2 Procedure and Results

The Return Circuit for Rail Voltage for the DCEE Rail System for the unbonded track condition is displayed in the FCM – Return Circuit Rail Voltage File Input – Return Circuit for Rail Voltage by Graphics screen.

It is more complicated than the case for the DC TEST Rail System.

The same screen displays the bonded rail case.
4.2.1 **Procedure**
The same steps are followed here as outlined in Section 2. These steps are not demonstrated here.

4.2.2 **Results**
The results are displayed as comparisons between the unbonded and bonded track cases. These comparisons are made at two levels, the first of which is **Maximum Rail Voltage** and the second is **Rail Voltage Profiles**.

4.2.2.1 **Maximum Rail Voltage Comparisons**
Maximum rail voltage comparisons are summarized in the next table.
Again the reduction of rail voltage in the track bonded case is obvious and is attributed to reduction of peak currents because of a higher conductivity return circuit.

<table>
<thead>
<tr>
<th>Rail Voltage Results - Cars per Train</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Maximum Rail Voltage</strong></td>
</tr>
<tr>
<td>Value</td>
</tr>
<tr>
<td>Position</td>
</tr>
<tr>
<td>Track Number</td>
</tr>
<tr>
<td>Node Name</td>
</tr>
<tr>
<td>Snapshot</td>
</tr>
<tr>
<td><strong>Peak Current</strong></td>
</tr>
<tr>
<td>Value</td>
</tr>
<tr>
<td>Position</td>
</tr>
<tr>
<td>Track Number</td>
</tr>
<tr>
<td>Train</td>
</tr>
<tr>
<td><strong>Minimum Voltage</strong></td>
</tr>
<tr>
<td>Value</td>
</tr>
<tr>
<td>Position</td>
</tr>
<tr>
<td>Track Number</td>
</tr>
<tr>
<td>Train</td>
</tr>
</tbody>
</table>
4.2.2.2 Rail Voltage Profiles

The Graphics package of the TOM has the capability of plotting Rail Voltage Profiles that are time-based rather than position-based. In contrast to what was done for the DC TEST Rail System, time-based rail voltage profiles are demonstrated here. Two plots of time-based rail voltage profiles are shown, one for unbonded rail and the other for bonded rail. In each case, the profile is shown at the position and track number of the maximum rail voltage for the no regeneration trains.

Unbonded Tracks
Bonded Tracks

5 Summary

A New Method of Rail Voltage Estimation has been added to the TOM. It now has the capability to estimate rail voltage using the actual return circuit of the rail system and is much more accurate than the old method.

This instruction manual provides a 11-step procedure for conducting rail voltage estimation.

This procedure is carried out for the DC TEST Rail System and several features of the 11-step method are illustrated in detail using the model. Screens are presented to provide a guideline to the user. Whereas the DC TEST Rail System is a simple two track railroad, the DCEE Rail System, which is a four track railroad with a wye, is also used to illustrate Rail Voltage Estimation.

Suggestions are made by presenting tables in EXCEL format on how to present Maximum Rail Voltage Conditions (Maximum Voltage Value, Maximum Voltage Position and Track Number and Time of Occurrence).

Rail Voltage Profiles, both position-based and time-based, are shown via the improved Rail Voltage Graphics package. These profiles are shown as plots for both rail systems considered.