TCRP C-24:
TRANSIT TRACTION POWER CABLES:
REPLACEMENT GUIDELINES

Kasim A. Korkmaz, PhD, Associate Professor, Eastern Michigan University
Evrim Dalkiran, PhD, Associate Professor, Wayne State University
Mohamed El-Gafy, PhD, PE, Associate Professor, Michigan State University

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Part I
Motivation, Objectives & Introduction
Motivation

- TCRP C24 ‘Replacement of Transit Traction Power Cables’ Project.

  - Develop a practical Guidebook for Transit agencies to share common and best practices.

  - Understanding the problems and providing practical solutions.

Objectives

Develop a guidebook for Traction Power Cables.

- The research includes a study of current practices for
  - Assessing insulation aging and
  - Replacement of cables before failure, including

  a) Approaches used in transit systems for which there are no monitoring programs and/or testing systems,
  b) Factors affecting life of cable, and
  c) Effective practices from transit agencies.
Introduction

- The structure of the guidebook as shown gives a detailed cable life evaluation and an optimized process to evaluate the lifespan of cables to inform practitioners and find a solution for their needs and problems in the industry.
• The work plan to develop the guidebook

Effective strategies, monitoring approaches and indications for the cables are critical to determine the end of life and replacement criteria for transit traction power cables.

• Maintaining,
• Upgrading,
• operating with Cost-Effective Strategies in optimum duration & period.

• The Strategic Management and Optimization for traction power cables has continuous and dynamic characteristics with many parameters related to

• Performance check,
• Optimization,
• Monitoring and process.

• System analysis for quality information
• Strength,
• Capacity and
• Performance analysis.
Part II
Answers to Key Questions

<table>
<thead>
<tr>
<th>Q1</th>
<th>How is the degree of degradation measured? What is the industry standard for degradation?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2</td>
<td>What is the lifespan of insulated cables?</td>
</tr>
<tr>
<td>Q3</td>
<td>What are the diagnostic indicators for when insulated cables should be replaced?</td>
</tr>
<tr>
<td>Q4</td>
<td>In what conditions will a cable achieve its maximum useful life?</td>
</tr>
<tr>
<td>Q5</td>
<td>What conditions will accelerate the degradation of a cable?</td>
</tr>
<tr>
<td>Q6</td>
<td>What strategies can be employed to extend the useful life of insulated cables?</td>
</tr>
</tbody>
</table>

Response: A measurement unit needs to be determined. For instance, for a mile in a highway, the degree of degradation can be a composite unit that includes the area of potholes, the number of potholes, and the distribution of depth of potholes. Similarly, a measurement unit should be defined for transit power cables.

Response: Current practices need to be determined to avoid failures with an accurate indication of replacement considering cost/benefit trade-off. Hence, we increase the lifetime of cables if we understand these reasons.

Response: The current environment and the best characterization of a “smart replacement strategy” for transit power cables needs to be defined. A practical, cost-effective construction environment should be set for a ‘smart replacement strategy’.
Answers to Key Questions

- Useful Life of Power Cables
- Degree of Degradation
- Detect Degradation of Power Cables
- Factors Influencing the Lifespan
- Cost-Effective Methods to Extend the Life Span
- Smart Replacement Strategy
- Installation Concerns
- Cable Failure Process

Useful Life of Power Cables

Major Causes of Failures are classified as:

- Manufacturing defects,
- Poor workmanship,
- External damages,
- Poor installation,
- Other aging factors,
- Thermal, electrical, mechanical, and environmental stresses

Cable Fault Mechanisms:
(a) Early Failure Caused by Poor Workmanship
(b) Poor Design Resulted in Accelerated Aging

(Aldhuwaian, 2015; Reid 2013)

<table>
<thead>
<tr>
<th>The Proportion of Failures</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint</td>
<td>37</td>
</tr>
<tr>
<td>Termination</td>
<td>32</td>
</tr>
<tr>
<td>Cable Body</td>
<td>31</td>
</tr>
</tbody>
</table>
Underground Cable
Insulation Materials Chart

Typical Construction of a Medium Voltage cable
(Levi and Shah, 2018)

Sample Traction Power Cables Examples

Cable Aging, Mechanisms, and Consequences
(Altamirano et al., 2010; Densley, 2001)
**Water Trees**
- are tree like patterns,
- branches through the wall of insulation,
- formed from water molecules,
- special dying techniques can make them visible.
- are often found in areas in the cable such as a bend.

**Electrical Treeing**
- Is similar in appearance to water trees.
- can be caused by voids, impurities, defects, or a combination of them.
- Often occur in locations of high electric stress.
- are usually visible to the naked eye if found within the insulation.
- are nearly impossible to catch with testing because once they form failure is quick to follow.
- can be affected by presence of foreign objects inside underground cable systems.

**Foreign Objects**
- The foreign object that makes its way into the insulation due to improper installation can change the distribution of the electric field causing there to be a higher stress area.

**Corrosion**
Corrosion is another agent that can cause Cable Rusting decomposition and failure or lead to other defects that can cause failure.

*(Lanz, 2017)*
*(Dodds, 2017)*
Overheating

• Effect on underground cable systems and cable joints.

Cable temperature depends on
• conductor and dielectric losses, installation environment (water, ground, air),
• thermal conductivity of the cable and surrounding material,
• ambient temperature, and other external sources of heat.

Installation Errors

• are the most common agent for cable system faults.
• are never found and it could take years before a fault occurs.
• fault when occurs is accompanied by an arc flash or explosion.

Examples for Overheated Cable
(Cloud, 2012)

Examples for Common Installation Errors
(Lanz, 2017)

Examples for Cable Failures

Joint Dissection, water Ingress (Neier, 2019)
Failures/Splice

The most degradation to the cables is caused by the changes in weather condition that includes but not limited to:

- Air moisture
- Temperature

To enhance the useful life of underground cables, many crucial actions can be taken into consideration, such as:

Considering the preexisting contamination and waterbodies when choosing the cables routes.

The water bodies may cause erosion around the cable lines which may lead to leakage into the cables.
The Power cables lifetime is generally estimated from the temperature change and associated lifetime reduction. Physical and visual inspections are the most common method of detection of failure (Gouveia, 2014).

Once degradation occurs in a cable, a failure of some degree will be the next step in the process. Once the cables fail, agencies make the decision for replace or repair.

Another decision for the agencies to make is when replace a cable due to the increasing age of the cables. Testing is a very useful tool to establish the overall scope of and the priority within a cable replacement program as “Repair or Replace” decision.

Ageing Factors

The ageing factors are described in the table.
### Cable Inspection Methods

**(Villaran and Lofara, 2009)**

**Visual Inspection**
- It is done by inspecting electrical cables by eye onsite, to assess any physical changes.
- It does not need any special equipment but must be performed by experienced personnel.

**Compressive Modulus**
- The compressive modulus can be defined as the stress-strain ratio below a proportional limit.
- Aging of cable insulation and jacketing material makes it harder and accordingly increases its compressive modulus.

**Dissipative Loss**
- It consists of dissipation factor test and the power factor test.
- The concept behind this test is when insulation material is degraded more leakage present.

**Insulation Resistance and Polarization Index**
- It includes the application of a current between the cable conductor and a ground to define the resistance of the insulation between them.

**Dielectric Loss**
- It consists of dissipation factor test and the power factor test.

**AC Voltage Withstand Test**
- A cable’s insulation is exposed to a high voltage in a very low frequency to determine if the insulation can withstand this high voltage.

**Partial Discharge Test**
- This test includes applying high voltage stress through a cable’s insulation to make partial discharge in the minor voids existing within the insulation.
- The occurrence of partial discharges shows the existence of degradation spots in the insulation.

**DC High Potential Test**
- The cable’s insulation is exposed to a high voltage potential to define if the insulation can survive a potential higher than anticipated in service for a particular period.

**Step Voltage Test**
- The cable’s insulation is exposed to voltage which begins low and is increased in stages until the maximum test voltage is reached.

**Time Domain Reflectometry**
- It has the same concept as radar.

**Infrared (IR) Thermography**
- It is done using a thermal detection system to measure the heat emitted by an object.

**Illuminated Borescope**
- This is considered as an enhanced visual test for inaccessible areas.

**Line Resonance Analysis (LRA)**
- It uses a waveform generator and analyzes electrical test signals to detect changes in the cable insulation’s properties.

### CONCLUSIONS

- The estimated lifetime of the underground power cables is around **35-40 years** based on the experimental findings.

- It is easier to test, repair the **overhead wirings** but requires more equipment deployment to detect faults in underground cables.

- **Repair or replacement** can be intense and complex decision.

- Fast and effective **cable failure detection** is critical.

- For the **age-related failure**, statistical approaches are used.

- **Health monitoring systems** are used in assessment, prediction and are helpful to determine the remaining lifetime of the cables.

- Most of the methods used to predict cable failures have been based on **historical failure data**.

- **Ageing and failure prediction relationship** is needed for the cable failure prediction models.
Summary for Literature Review

• There is a good amount of research work completed for cables in the literature.

• The findings are summarized in the Guidebook.

<table>
<thead>
<tr>
<th>Useful Life of Power Cables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhao et al. (2017)</td>
</tr>
<tr>
<td>Balossier (2010)</td>
</tr>
<tr>
<td>Ahrabani et al. (2011)</td>
</tr>
<tr>
<td>Lévy (2011)</td>
</tr>
<tr>
<td>Mulhearn and Hendricks (2006)</td>
</tr>
<tr>
<td>Lévy (2011), Dassault</td>
</tr>
<tr>
<td>Lévy et al. (2011)</td>
</tr>
<tr>
<td>Govor (2012)</td>
</tr>
<tr>
<td>Lévy (2011)</td>
</tr>
</tbody>
</table>

Degree of Degradation

Chen et al. (2016)     Give the predictive model of the degradation of cable insulators subject to radionics and chemics.
Liu (2011)            The thermal degradation rate is determined from fitting experimental data to a physical-based equation.
Wang (2010)           The method of degradation measurement and prediction of parameters and the dynamic measurement are an open issue.
Nikam et al. (2011)   The degradation process causes the deterioration of the outer insulation layer which can be prevented to some extent by catalytic protection against the cable metallic screen surfaces.

Semi-Degradation of Power Cables

Mishra et al. (2012)  Built a learning model (BMD) and used to assess a cable system's health and to evaluate maintenance strategies.
Sinha et al. (2018)   Developed a probabilistic dynamic programming algorithm to find the optimal maintenance policy for power cables using the degradation rate and failure distribution of cables.
Cottam et al. (2010)  Used artificial intelligence (Artificial Neural Networks (ANN)) to predict the failure history of cables.
Kushwaha et al. (2018) Proposed a model for the propagation velocity of the cable and determined experimentally to analyze locating faults on MM fibers with increasing accuracy.
Zhang et al. (2008)   Proposed a strategy of utilizing saw-tooth resonance excitation to accurately detect the type and degree of cable failures.
Cottam et al. (2012)  Application of non-linear time-series optimization for the thermal performance optimization of the underground power cable system.
Houshangi (2017)     The replacement of old cables and the implementation of improved cable systems as a result of existing cable sites and network changes.
Ismail et al. (2016)  The effects of control cables, repeater communications, on failure into evaluation a stipulated.

Part III
Survey & Interviews
Data collection process was carried out with transit agencies and practitioners in the industry with survey study and case studies.

<table>
<thead>
<tr>
<th>Region</th>
<th>System Size</th>
<th>&lt;40-60</th>
<th>System Duration</th>
<th>System Length (miles)</th>
<th>DC</th>
<th>AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-West</td>
<td>Small</td>
<td>Very Old/90s</td>
<td>1975s</td>
<td>50</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Northeast</td>
<td>Very Large</td>
<td>New 2000</td>
<td>2005</td>
<td>625</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Ohio Valley</td>
<td>Large/90s</td>
<td>New</td>
<td>2000</td>
<td>1000</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>West</td>
<td>Medium</td>
<td>Old</td>
<td>1985</td>
<td>42.2</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>The South</td>
<td>Large/90s</td>
<td>Old/90s</td>
<td>1960s</td>
<td>33.4</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Central</td>
<td>Large</td>
<td>Old/90s</td>
<td>1975s</td>
<td>325</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Mid-Atlantic</td>
<td>Medium/old</td>
<td>Old/90s</td>
<td>1973</td>
<td>14</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Ohio Valley</td>
<td>Large/10</td>
<td>Old/90s</td>
<td>1955</td>
<td>30</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>The South</td>
<td>Large/10</td>
<td>Very Old/90s</td>
<td>1980</td>
<td>35</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Northeast</td>
<td>Medium/10</td>
<td>Very Old/90s</td>
<td>1990</td>
<td>35</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>West</td>
<td>Very Large/90s</td>
<td>New to Old/75</td>
<td>2000-2015</td>
<td>200-500</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Ohio Valley</td>
<td>Very Large/200</td>
<td>Old</td>
<td>205</td>
<td>220</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Northeast</td>
<td>Very Large/100</td>
<td>Old</td>
<td>1990</td>
<td>247</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Ohio Valley</td>
<td>Very Large/750</td>
<td>Old and New</td>
<td>1900-1990</td>
<td>225</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>South</td>
<td>Medium/21</td>
<td>New/5 years</td>
<td>2014</td>
<td>22.7</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>North west</td>
<td>Large/62</td>
<td>Old/90</td>
<td>1916</td>
<td>62</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Northeast</td>
<td>Large/74</td>
<td>Old/90</td>
<td>1980-1990</td>
<td>34.45</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Mid-Atlantic</td>
<td>Large</td>
<td>very old</td>
<td>1975s</td>
<td>325</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

2. What type and size of transit power cables are used?

- Type and Size of Transit Power Cables Used in the System.
1. How many taps per hundred feet are in your cables? What is the maximum number of taps allowed per circuit?

2. What is the expected useful lifetime of cables that you use? Do you follow any practices to increase the useful life of the cables?

Steps to maximize cable life:
1. Design to minimize heating of cables due to overload
2. Design to minimize damage during installation (large bend radii, pull boxes less than 500' apart)
3. Ensure cables and taps are kept dry
4. What are the environmental factors such as temperature, animals (birds, rodents), water, above or below the water level, etc. affecting the useful life of transit power cables?

Environmental Factors

5. What are the physical parameters affecting the cable design including jacketing, insulation, duct bank?

The following statements are some critical notes from the responders in the survey responds to classify the physical parameters altering the useful life of transit power cables:

- “Cable insulation/jacket designed for wet locations.”
- “Insulation rated for well above system voltage to handle transient surges.”
- “Properly designed duct bank (drainage, depth) to maintain dry and cool cables.”
- “Proper separation and support of cables in manholes.”
- “Design duct bank for minimal cable-pulling stress (broad sweeps, frequent pull boxes).”
6- How do you determine the degree of degradation of insulated cables? Do you have cable monitoring systems?

Degree of degradation monitoring systems

7- Is there a lifetime guarantee by the suppliers? Are there any maintenance, testing, replacement schedules suggested by the supplier?

Lifetime Guarantee
8- What are the **diagnostic tests** being carried out on transit cables? **How often** do you need to run these tests?

- **Diagnostic Test Types**
- **Inspection Frequency**

9- What is the **crew size**?
10. Do you practice any **cable inspection** and **maintenance procedures**? If so, please describe your procedures including intervals and types.

- **Inspection Frequency**
  - Annually: 8
  - Biannually: 5
  - Randomly: 3

- **Types of Tests**
  - Visual inspection: 2
  - Earthquake resistance: 1
  - Transmitter inspection: 3
  - Thermography: 2
  - Punching manifold: 1
  - Procedures by United Authorities: 1

11. Under what circumstances, do you choose repairing the cable in comparison to replacing?

- Circumstances for choosing **Repair over Replacement**
  - connections: 6
  - tap & manholes: 5
  - insulation: 3
  - corrosion: 5
  - funding: 1
  - leakage: 2
  - size of cable: 4
  - accessibility of cable: 3
12. Is there any replacement strategy including "Smart Replacement Strategy" that you are implementing for insulated cables?

13. Do you have to stop operations completely during repair and replacement?

Stopping Operation Completely During Repair or Replacement

Distribution of factors stopping the operations
14- Were there any failures being experienced by your agency? Are the reasons behind the failures known? How do you diagnose failures?

Distribution of Experiencing Failure

Failed

Diagnosis Methods

Failure Reasons

Statistical Analysis

Correlation Results for Monitoring Systems and Replacement Strategies

<table>
<thead>
<tr>
<th>Replacement Strategy</th>
<th>Yes</th>
<th>No</th>
<th>Total</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring System</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>9</td>
<td>5</td>
<td>14</td>
<td>0.18</td>
</tr>
<tr>
<td>No</td>
<td>11</td>
<td>24</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>11</td>
<td>29</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

- the Fisher’s Exact test revealed that using a cable replacement strategy did not significantly change by using a monitoring system ($p>0.05$). The significance level ($p$) was found as 0.18. Out of the 35 responders who do not have a cable monitoring system
Content Analysis

- Survey study is formed with open ended questions.
- Content analysis of the survey results to determine the presence of certain words, themes, or concepts within some given qualitative data.

Content Analysis Methodology

Sample for Q4 Environmental Factors Affecting Cables
A Summary for Survey Answers

<table>
<thead>
<tr>
<th>#</th>
<th>Question</th>
<th>Most Common Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Data collection process</td>
<td>Participants were selected from various locations to define their processes.</td>
</tr>
<tr>
<td>2</td>
<td>Type and size of busway power cables</td>
<td>Sizes range from 250 MCM to 5000 MCM, with the most popular sizes being 500 MCM, 700 MCM, and 1000 MCM.</td>
</tr>
<tr>
<td>3</td>
<td>How many taps per hundred feet</td>
<td>From a tap to 10 taps per circuit.</td>
</tr>
<tr>
<td>4</td>
<td>Minimum number of taps</td>
<td>Spacing between taps is 100 ft to 1000 ft.</td>
</tr>
<tr>
<td>5</td>
<td>Environmental parameters affecting the useful life of busway power cables</td>
<td>Two most-cited factors are water and temperature.</td>
</tr>
<tr>
<td>6</td>
<td>Physical properties of the busway design</td>
<td>Including and conduct isolation.</td>
</tr>
<tr>
<td>7</td>
<td>Determine the degree of degradation</td>
<td>Include the Magnus test, visual inspection, and a “Ask to Fail” method.</td>
</tr>
<tr>
<td>8</td>
<td>Cable monitoring systems</td>
<td>Only 6% of the participants have stated that they have a monitoring system.</td>
</tr>
<tr>
<td>9</td>
<td>A warranty guaranteed by the supplier</td>
<td>There is no warranty guarantee by suppliers.</td>
</tr>
<tr>
<td>10</td>
<td>Maintenance, testing, and replacement schedules suggested by the supplier</td>
<td>Suppliers provide support to operators in case any problems occur.</td>
</tr>
<tr>
<td>11</td>
<td>Diagnostic tests carried out on busway</td>
<td>Magnets, Skid-Test, and D. Testing are the most regularly implemented.</td>
</tr>
<tr>
<td>12</td>
<td>How to you start these tests</td>
<td>Forages, generally conduct diagnostic tests when a failure occurs.</td>
</tr>
<tr>
<td>13</td>
<td>Cores on each tap type that includes the quantity of operations and test length</td>
<td>Core components have up to five people.</td>
</tr>
<tr>
<td>14</td>
<td>Opportunity for test operations</td>
<td>Many have the potential to damage the cable.</td>
</tr>
<tr>
<td>15</td>
<td>Cable inspection and maintenance procedures</td>
<td>Over half of the respondents to question 10 indicated that they did not have established inspection and maintenance procedures.</td>
</tr>
</tbody>
</table>

# Questions | Most Common Answers |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>What types of repairs are made</td>
</tr>
<tr>
<td>12</td>
<td>Under what circumstances, choose replacing the cable in comparison to repairing</td>
</tr>
<tr>
<td>13</td>
<td>Diagnostics indicators for replacing insulated cables</td>
</tr>
<tr>
<td>14</td>
<td>General costs and duration of repair and replacement</td>
</tr>
<tr>
<td>15</td>
<td>Is there any replacement strategy including “Smart Replacement Strategy”</td>
</tr>
<tr>
<td>16</td>
<td>Do you have to stop operations completely during repair and replacement</td>
</tr>
<tr>
<td>17</td>
<td>Failures being experienced</td>
</tr>
<tr>
<td>18</td>
<td>Are reasons behind the failures known?</td>
</tr>
<tr>
<td>19</td>
<td>How do they diagnose failures?</td>
</tr>
<tr>
<td></td>
<td>* Visual Inspection</td>
</tr>
<tr>
<td></td>
<td>* Continuous Monitoring</td>
</tr>
<tr>
<td></td>
<td>* Rate-of-Rise (ROR)</td>
</tr>
<tr>
<td></td>
<td>* Hi-pot</td>
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Part IV.
Case Studies

Case Study Map

- Case Study 1: Greater Cleveland Regional Transit Authority
- Case Study 2: New Orleans Regional Transit Authority
- Case Study 3: Bay Area Rapid Transit
- Case Study 4: New York City Transit
- Case Study 5: Amtrak’s Replacement Case
- Case Study 6: Tri-County Metropolitan Transportation District of Oregon
- Case Study 7: Utah Transit System
- Case Study 8: Maryland
- Case Study 9: Washington Metropolitan Area Transit Authority
- Case Study 10: Minnesota Metro Transit
Interview Process Flowchart for the Case Studies

- Questionnaire Development
- Research Panel Feedback
- Pilot Testing
- Questionnaires Modification
- Interview Time Set-up
- Email Interview Instrument
- Or Field Interview
- Follow-up & Collect Artifacts
- Documentation

Case Study 1: Greater Cleveland Regional Transit Authority

<table>
<thead>
<tr>
<th>Concept</th>
<th>Current Practice</th>
</tr>
</thead>
</table>
| Quick Fix | A weekly rolling visual inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects. A monthly rolling inspection is performed in which maintenance workers review the OCS for defects.
Cost Determination

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure or unplanned interruption cost</td>
<td>Average hourly power consumption (L&lt;sub&gt;h&lt;/sub&gt;)</td>
</tr>
<tr>
<td></td>
<td>Average unplanned interruption time in hours (h)</td>
</tr>
<tr>
<td></td>
<td>Power outage Costs (A)</td>
</tr>
<tr>
<td></td>
<td>Time-dependent power outage cost (h&lt;sub&gt;2&lt;/sub&gt;)</td>
</tr>
<tr>
<td></td>
<td>Average failure costs (C&lt;sub&gt;a&lt;/sub&gt;)</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>The average cost of diagnostic tests and inspections is negligible as compared to repair and replacement cost</td>
</tr>
<tr>
<td>Repair cost</td>
<td>Average maintenance cost for cables (C&lt;sub&gt;m&lt;/sub&gt;)</td>
</tr>
<tr>
<td>Cost of replacement</td>
<td>Cost of new cable (C&lt;sub&gt;n&lt;/sub&gt;)</td>
</tr>
<tr>
<td></td>
<td>Cost of installation (C&lt;sub&gt;n&lt;/sub&gt;)</td>
</tr>
<tr>
<td></td>
<td>Replacement cost of cable (C&lt;sub&gt;n&lt;/sub&gt;)</td>
</tr>
</tbody>
</table>

What are the general costs and durations of repair and replacement? *Survey Responses*

- Vary
- It can be done in house or need a contractor. Could be days or a week or more. Cost driven by not having in stock and need contractor
- 10k to 40k, mostly labor
- It all depends on the type and extent of the defect

Any cost-effective application you practice for repair and replacement? *Survey Responses*

- It’s mostly about time, not cost
- Not sure
- When possible we remove underground taps

Table 4.3, New Orleans Regional Transit Authority

<table>
<thead>
<tr>
<th>Concept</th>
<th>Current Practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quick view</td>
<td></td>
</tr>
<tr>
<td>Degree of Degradation</td>
<td></td>
</tr>
<tr>
<td>Diagnostic Indicators</td>
<td></td>
</tr>
<tr>
<td>Effecting Factors</td>
<td></td>
</tr>
<tr>
<td>Replacement Strategies</td>
<td></td>
</tr>
</tbody>
</table>

Case Study 2: New Orleans Regional Transit Authority
Cables used in New Orleans Agency

Tap connectors for aluminum cables

Taps Created by the Agency

New Orleans Regional Transit Authority

Tap connectors used in the Agency
Agency Responses to the Critical Problems I

Case Study 6: Tri-County Metropolitan Transportation District of Oregon

Table 4.18: Tri-County Metropolitan Transportation District of Oregon

<table>
<thead>
<tr>
<th>Length (miles)</th>
<th>Age (years)</th>
<th>Electrification system (voltage, current, type of contact, contact system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Team (contractor, facility)</td>
<td>Light rail</td>
<td>Light rail</td>
</tr>
<tr>
<td>Rapid transit service, underground</td>
<td>Commuter rail</td>
<td>Other (Please state the reason)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Concept</th>
<th>Current Practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quick note</td>
<td>They typically do a hard visual inspection on cables during the energized process. They do a visual inspection on feeder cables made by the contractor during annual track safety binder inspections.</td>
</tr>
<tr>
<td>Degree of Degradation</td>
<td>Degradation has not been something they have been able to quantify. No cable monitoring system is in use.</td>
</tr>
<tr>
<td>Diagnostic Indicators</td>
<td>In the past, they had been using insulation resistance by meggering, but results were varied, and failures occurred on supposedly good cables, so currently they use a “go to fail” method.</td>
</tr>
<tr>
<td>Summary</td>
<td>There is no replacement strategy. Only during the actual replacement work, when they try to do during non-service hours or in coordination with other work outings. The failed cable can be taken out of service and operations can resume.</td>
</tr>
<tr>
<td>Replacement Strategy</td>
<td>N/A existing</td>
</tr>
</tbody>
</table>

Review and Update

Considerations in practice: Cable life, Cable failure modes, Installation considerations, Environmental issues, Manufacturability, and Cost.

Examples:

In Figures 4.11 to 4.16, samples physical and material damages are presented. Figures 4.11, 4.12, and 4.16 give the agency responses. Questions were sent to agencies and answers were collected and the responses were shared in Figures 4.11 and 4.12.

In Figures 4.11 to 4.16, construction practices are presented. Figure 4.16 gives the cable failure scenario. Figure 4.19 presents Fail to Ground Voltage Notice and Figure 4.19 presents O CSP Details. Figure 4.19 presents Electrification Details.
Agency Responses to the Critical Problems II

Construction Practices
Cable Samples

Overhead Cable Connection Samples
Cable Damages

Physical Cable Damage  Animal Damage  Damaged Cable Sample

Failure and Repair Samples
Experienced Cable Failure Examples

Megger Test

1. Contact Control for Substation entry and to take Substation off-line.

2. Open and trip out Feeder Breakers.

3. Open corresponding pole top switches

4. Test buss for "0" voltage.

5. Apply personal protective grounds to buss and disconnect surge arrester.

6. Remove personal protective ground

7. Megger cables at 1kv.
### Sunset #23 Cable Megger Log

<table>
<thead>
<tr>
<th>Date</th>
<th>F1 Cables (Ω)</th>
<th>F2 Cables (Ω)</th>
<th>F3 Cables (Ω)</th>
<th>F4 Cables (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/30/2006</td>
<td>6.8</td>
<td>7.5</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>7/6/2007</td>
<td>8.1</td>
<td>9.3</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>7/23/2008</td>
<td>7.6</td>
<td>8.9</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>7/23/2009</td>
<td>7.2</td>
<td>9.2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>10/31/2011</td>
<td>2.12</td>
<td>2.4</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>10/18/2012</td>
<td>1.8</td>
<td>4.5</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>10/28/2013</td>
<td>2.5</td>
<td>2.4</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>10/30/2014</td>
<td>1.4</td>
<td>1.8</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>4/25/2017</td>
<td>2.2</td>
<td>4.0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>4/28/2018</td>
<td>2.7</td>
<td>4.5</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### Hawthorn Farm #34 Cable Megger Log

<table>
<thead>
<tr>
<th>Date</th>
<th>F1 Cables (Ω)</th>
<th>F2 Cables (Ω)</th>
<th>F3 Cables (Ω)</th>
<th>F4 Cables (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/10/2007</td>
<td>3.0</td>
<td>6.7</td>
<td>N/A</td>
<td>10.6</td>
</tr>
<tr>
<td>12/10/2008</td>
<td>3.0</td>
<td>6.7</td>
<td>N/A</td>
<td>10.6</td>
</tr>
<tr>
<td>9/22/2009</td>
<td>3.8</td>
<td>6.7</td>
<td>N/A</td>
<td>10.6</td>
</tr>
<tr>
<td>9/29/2008</td>
<td>4.9</td>
<td>6.7</td>
<td>N/A</td>
<td>10.6</td>
</tr>
<tr>
<td>9/22/2009</td>
<td>2.2</td>
<td>6.7</td>
<td>N/A</td>
<td>10.6</td>
</tr>
<tr>
<td>5/11/2011</td>
<td>2.3</td>
<td>6.7</td>
<td>3.1</td>
<td>3.1</td>
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<tr>
<td>7/23/2011</td>
<td>3.1</td>
<td>6.7</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>7/23/2011</td>
<td>1.4</td>
<td>6.7</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>7/23/2011</td>
<td>1.3</td>
<td>6.7</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>7/23/2011</td>
<td>2.3</td>
<td>6.7</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>1/1/2014</td>
<td>2.1</td>
<td>6.7</td>
<td>3.1</td>
<td>3.1</td>
</tr>
</tbody>
</table>
Table 4.26. Maryland Transit System

<table>
<thead>
<tr>
<th>Length (Maid.)</th>
<th>Age (yrs.)</th>
<th>Electrical System (volts, current, type, contact system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light rail</td>
<td>34</td>
<td>29</td>
</tr>
<tr>
<td>Rigid transit (metro, subway, underground)</td>
<td>15</td>
<td>49</td>
</tr>
<tr>
<td>Commuter rail</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (Please note the year)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Quick facts:
- Tests use 1000/6624 twin-core power cables, creating 2 (one 1000/6624 cable per track). Cables are connected to the testing power source. 3. In addition, the cable is secured to the structural support system to ensure it does not move. 4. Testing Procedure Details are given in Figure 4-10.
- Testing Procedure Details are given in Figure 4-10.
- Testing Procedure Details are given in Figure 4-10.

Case Study 8: Maryland Transit System

MTA Testing Procedure Details

- They perform a visual inspection of the cable and conduct a thorough visual inspection of the cable. This is performed at the end of every fiscal year.
- They perform a thorough visual inspection of the cable at the end of every fiscal year. This is performed at the end of every fiscal year. This is performed at the end of every fiscal year.
- They perform a thorough visual inspection of the cable at the end of every fiscal year. This is performed at the end of every fiscal year. This is performed at the end of every fiscal year.
- They perform a thorough visual inspection of the cable at the end of every fiscal year. This is performed at the end of every fiscal year. This is performed at the end of every fiscal year.
Case Study 9: Washington Metropolitan Area Transit Authority

<table>
<thead>
<tr>
<th>Findings</th>
<th>Required Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple WMATA departments are responsible for critical TPE system inspection, maintenance, and repair activities, preventing clear ownership of the TPE system and identifying systemic issues and priorities.</td>
<td>WMATA must conduct an assessment to determine if all TPE system program components should be integrated into a single department with sole responsibility for managing, inspecting, maintaining, repairing, and upgrading the TPE system. At a minimum, this assessment must include those elements of TPE system inspection, maintenance, and repair currently performed by TRPA, third rail inspection and maintenance work currently performed by TRST, negative return system inspection and maintenance activities performed by ATC, cable replacement activity performed by IRCC, engineering services provided by PWSA, and lock-out/tag-out procedures implemented by the ROCC and MOC.</td>
</tr>
<tr>
<td>WMATA ROCC and MOC personnel are not sufficiently proactive in managing TPE concerns during emergencies.</td>
<td>Emergency Removal and Restoration of Third Rail Power Masline to consider: 1) removal of power during smoke conditions, especially with corresponding third rail power outages caused by unknown conditions, and 2) a requirement to de-energize third rail power at the adjacent power substation or tie breaker, provided the situation does not strand a train that needs to be moved from the smoke condition.</td>
</tr>
<tr>
<td>Insufficient resources are available to support the testing, inspection, and maintenance of WMATA's TPE system.</td>
<td>WMATA must evaluate options for using contracts to complete its TPE system corrective maintenance backlog and outstanding preventive maintenance requirements in the near-term and implement results.</td>
</tr>
<tr>
<td>Traction Power Cables</td>
<td>Traction power cables are often loose on the ground, subjecting them to contamination, vibration, and damage from movement.</td>
</tr>
<tr>
<td>Negative Return System</td>
<td>WMATA does not implement a consistent program regarding its negative return system's testing, inspection, and maintenance.</td>
</tr>
<tr>
<td>Insulation Resistance</td>
<td>WMATA does not currently test cables to ensure insulation resistance.</td>
</tr>
<tr>
<td>Examples</td>
<td>Power Cable conditions and various stages are presented in Figure 4.13.</td>
</tr>
</tbody>
</table>
# Traction Power Electrification System Investigation

## Cable Conditions

- a. Cable Plant Visible during Silver Line Construction
- b. Cable and Connector Assembly Covered in Mud and Water
- c. Power Cable in Tunnel Floor in Damp and Moody Conditions
- d. Cable on the Ground
- e. Power Cables Leaked against Tunnel Wall
- f. Typical Repair for Securing Cable Off the Ground

## Summary Chart for Case Studies

<table>
<thead>
<tr>
<th>Case Study</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat increase observed</td>
<td></td>
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<tr>
<td>Visual inspections</td>
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<tr>
<td>Measuring and threshold tests</td>
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<tr>
<td>Insulation resistance and no-potential test</td>
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<tr>
<td>Partial discharge diagnostics</td>
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<tr>
<td>No test (Run-to-Fail)</td>
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<tr>
<td>Temperature</td>
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<td>Tearing</td>
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<tr>
<td>Water damage</td>
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<tr>
<td>Degradation in insulation level</td>
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<td>Aging</td>
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<tr>
<td>Cable Replacement Strategies</td>
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<tr>
<td>When cable failures have a major impact to the operation</td>
<td>•</td>
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<tr>
<td>Smart replacement system</td>
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<tr>
<td>Part of substation removal projects</td>
<td>•</td>
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<tr>
<td>Techniques to Enhance Cable Lifespan</td>
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<tr>
<td>Cable-jacketing</td>
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<td></td>
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<tr>
<td>Specially designed taps</td>
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<tr>
<td>PVC sealing</td>
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</tbody>
</table>
Part V.
Cable Replacement

- In this section, an Optimization Process and Finite Element Analysis were carried out.
- The factors included to estimate the cable failure rate were defined.
- Historical data and cable features are discussed.
Overview of the Analytics

1. Data Collection for Descriptive Analytics
   - 1.1. Cable Capital
   - 1.2. Historical Failure Data
   - 1.3. Testing and Preventive Maintenance Data

2. Predictive Analytics
   - 2.1. Estimate Cable Test Results
   - 2.2. Estimate Failure Rates

3. Prescriptive Analytics
   - 3.1. Testing Schedule
   - 3.2. Preventive Maintenance, Replacement Schedules
1. Data Collection for Descriptive Analytics

1.1. Cable Capital

- Location
- Installation Year
- Cable Function
- Length
- Conduit
- Insulation type
- Jacketing
- Low smoke zero halogen
- Presence of water
- Exposure to extreme temperatures
- Underground /overhead
- Testing Frequency (per year)
- Test type
- Last test date
- Last test result
- Scheduled test date

Banfield  EPR  XLPE  Yes  2KV  1987  400ft  Moderate  Low  Low  UG  1.0
Fuller    EPR  XLPE  Yes  2KV  2009  1000ft High  Low  Low  UG  1.0
Lincoln   EPR  XLPE  Yes  2KV  2009  350ft  Low  Low  Low  UG  1.0
East Portal EPR  XLPE  Yes  2KV  1998  250/3150ft Moderate  Low  Low  UG/PUF  1.0
Bybee     EPR  XLPE  Yes  2KV  2015  600ft  High  Low  Low  UG  1.0
Sunset    EPR  XLPE  Yes  2KV  1998  400ft  Low  Low  Low  UG  1.0
Mt. Hood  EPR  XLPE  Yes  2KV  2001  400ft  High  Low  Low  UG  1.0
Steel Br. EPR  XLPE  Yes  2KV  1986  1000/1850ft Moderate  Moderate  Low  UG/PUF  1.0
Parkrose  EPR  XLPE  Yes  2KV  2001  850ft  Low  Low  Low  UG  1.0
Gateway  EPR  XLPE  Yes  2KV  1998  1000ft  Low  Moderate  Low  UG  1.0
1. Data Collection for Descriptive Analytics

1.2. Historical Failure Data

- Cable ID
- Location
- Date of failure
- Emergency status
- Failure mode
- Aggravating factors
- Date of repair
- The number of previous repairs
- Time to repair the cable
- Cost of materials
- Cost of labor
- System downtime cost
- Other costs
- Replace or Repair

1.2. Historical Failure Data Example

<table>
<thead>
<tr>
<th>Failure #</th>
<th>Location</th>
<th>Date of Failure</th>
<th>Cost of repair/Replace</th>
<th>Downtime Cost</th>
<th># of previous repairs</th>
<th>Failure Mode /If known</th>
<th>Aggravating Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5th Market</td>
<td>07/11/2014</td>
<td>$15,000</td>
<td>$0</td>
<td>None</td>
<td>Corrosion</td>
<td>Bad Tap</td>
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<tr>
<td>2</td>
<td>32nd</td>
<td>02/06/2016</td>
<td>$9,086</td>
<td>$0</td>
<td>None</td>
<td>Corrosion</td>
<td>Bad installation</td>
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<tr>
<td>3</td>
<td>East Portal</td>
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<td>$9,125</td>
<td>Yes</td>
<td>None</td>
<td>Insulation Failure</td>
<td>Damage on Installation</td>
</tr>
<tr>
<td>4</td>
<td>Hillsboro</td>
<td>04/25/2018</td>
<td>$8,280</td>
<td>Yes</td>
<td>None</td>
<td>Insulation Failure</td>
<td>Damage on Installation</td>
</tr>
<tr>
<td>5</td>
<td>6th Mad</td>
<td>03/12/2019</td>
<td>$18,169</td>
<td>Yes</td>
<td>None</td>
<td>Insulation Failure</td>
<td>Damage on Installation</td>
</tr>
</tbody>
</table>
1. Data Collection for Descriptive Analytics

1.3. Testing and Preventive Maintenance Data

- Cable ID
- Test date
- Test type
- Test result
- Cable state classification (Excellent, Good, Fair, Needs replacement)
- Cost of test

### 1.3. Testing and Preventive Maintenance Data Example

<table>
<thead>
<tr>
<th>DATE</th>
<th>Feeder 1 (Ω)</th>
<th>Feeder 2 (Ω)</th>
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</thead>
<tbody>
<tr>
<td>2/15/2006</td>
<td>1 Min 1.3G</td>
<td>1.3G</td>
</tr>
<tr>
<td></td>
<td>3 Min 1.4G</td>
<td>1.4G</td>
</tr>
<tr>
<td></td>
<td>5 Min 1.4G</td>
<td>1.4G</td>
</tr>
<tr>
<td>3/5/2008</td>
<td>1 Min 1.2G</td>
<td>1.2G</td>
</tr>
<tr>
<td></td>
<td>3 Min 1.3G</td>
<td>1.4G</td>
</tr>
<tr>
<td></td>
<td>5 Min 1.4G</td>
<td>1.3G</td>
</tr>
<tr>
<td>6/4/2010</td>
<td>1 Min 1.2G</td>
<td>1.15G</td>
</tr>
<tr>
<td></td>
<td>3 Min 1.36G</td>
<td>1.23G</td>
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<tr>
<td></td>
<td>5 Min 1.41G</td>
<td>1.26G</td>
</tr>
<tr>
<td>2/22/2011</td>
<td>1 Min 1.25G</td>
<td>1.23G</td>
</tr>
<tr>
<td></td>
<td>3 Min 1.35G</td>
<td>1.25G</td>
</tr>
<tr>
<td></td>
<td>5 Min 1.5G</td>
<td>1.27G</td>
</tr>
<tr>
<td>6/12/2014</td>
<td>1 Min 1.26G</td>
<td>1.13G</td>
</tr>
<tr>
<td></td>
<td>3 Min 1.30G</td>
<td>1.20G</td>
</tr>
<tr>
<td></td>
<td>5 Min 1.35G</td>
<td>1.23G</td>
</tr>
</tbody>
</table>
2. Predictive Analytics

2.1. Estimate Cable Test Results
- Test type
- Cable age
- Jacket type
- Insulation type
- Conduit
- Previous test results

2.2. Estimate Cable Failure Rates
- Exponential, Power, Linear Function
- Cable age
- Jacket type
- Insulation type
- Conduit type

The estimation of failures

(B) Expected number of failures from cable installation to age 80

(A) The failure rate from cable installation (t = 0) to age 80
3. Prescriptive Analytics

3.1. Testing Schedule

Inputs
- Cable capital
- Time required for testing
- Number of technicians
- Other assignment restrictions (time of the day for testing, etc.)

Output
- Test schedule for technicians, where
  - All cables are tested
  - Fairly distributed workload among technicians
  - Uniform workload (avoid bottlenecks)
  - Repetitive test schedule

3.2. Cable Replacement

Inputs
- Estimated cable failure rate function
- Cost of failure
- Cost of replacement

Output
- Optimal time to replace the cable

Data Challenges
- Estimating cable failure rate
  - Data is not available
  - Failures are rare events, data accumulation is very slow
- Estimating cost of failure
  - Large variation in the cost of service interruption, cost of losing customer goodwill
- Estimating cost of replacement
  - Many variables affecting the cable cost (jacketing, insulation, conduit, etc.)
  - Affect of economies of scale (replacing multiple cables)
3. Prescriptive Analytics

3.2. Cable Replacement

As cable ages:

- Failure cost per year increases
- Average replacement cost per year decreases
- Total cost decreases first, and then increases

Data Challenges

- Estimate cost of replacement relative to the cost of failure: 1-to-1, 1-to-10, etc.
- Conduct sensitivity analysis using different parameter values and functions for failure rate function
Process for Determining Optimal Cable Replacement Period

1. All cable failures should be collected using a secure online database to estimate cable failure rates. Each failure record should include the following information: insulation type, jacket type, conduit, rated voltage, cable age, presence of water, exposure to extreme temperatures, underground/overhead, length of the power cable segment, the number of previous repairs on the cable, maintenance period.

2. For each link on each network, if possible
   a. Cable repair cost should be estimated (material, labor, etc.).
   b. Cable failure cost should be estimated (repair cost and cost due to loss of passengers).
   c. Cost of cable replacement should be estimated (material, labor, loss of passengers, other costs).

   Otherwise, the ratio between failure and replacement costs is estimated based on historical data or expert opinion.

3. Average of optimal cost and optimal cable replacement period ($T_r^*$) are found by calculating average total cost for $T = 1, \ldots, 80$.

4. Identify groups of cables (two or more) that requires the closure of the same transportation lane and are in close proximity to each other. Identify the replacement cost of the group of cables and check if cases a or b in Equations (5.10) and (5.11) holds true. Accordingly, determine whether replacing group of cables together is cost effective or not.

Finite Element Analysis
Finite Element Modelling

Stress Distribution under Tension, Torsion and Thermal Loadings
Part VI.
Conclusions

Conclusions

This guidebook has been prepared as a result of the TCRP C-24 research project.

The significant results:
• Produced a guidebook,
• A detailed investigation for Traction Power Cables,
• A detailed Literature review was carried out,
• Key questions have been determined and answered,
• A Survey study was carried out to define the current practices,
• Case studies were carried out for various locations for a detailed investigation,
• An Optimization Model was developed,
• Finite Element Analysis was carried out.
Conclusions

- The guide book presents practical solutions for the problems faced by the agencies.
- Problems and solutions created by the agencies are shared in the guidebook to share the best practices.
- Sections are designed to help practitioners to get an organized and systematic guide for the traction power cables.

Part VII.
Discussion
Thanks,

Please contact me for any further information or any detail you want to discuss.
Kasim Korkmaz
kkorkmaz@emich.edu

Please fill the Exit Survey to give us feedback and to keep in touch:
https://forms.gle/2N9CSs8MbX9tLpS87