TCRP TRANSIT COOPERATIVE RESEARCH PROGRAM

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

Zoom Meeting

https://emich.zoom.us/j/87655977752?pwd=VmtzQ0JnVk1hQW1QR0tJOW9RdEE4dz09

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January 14th, 2022
12:00 pm - 2:00 pm EST

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Outline

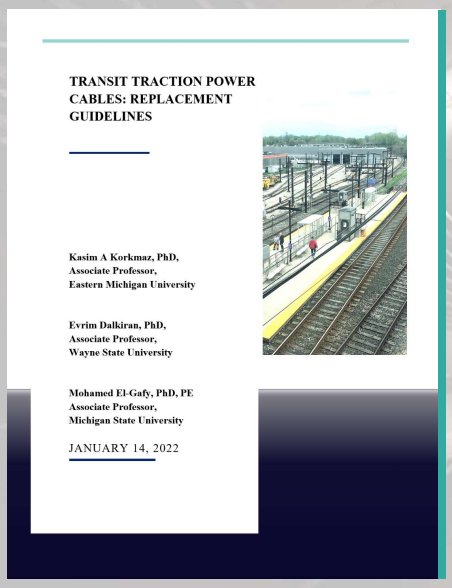
- Part I. Motivation, Objectives & Introduction
- Part II. Answers to Key Questions
- Part III. Survey & Interviews
- *A Short Break*
- Part IV. Case Studies
- Part V- Cable Replacement
- Part VI – Conclusion
- Part VII. Discussion

About Today's Meeting

Two-hour Session with one break

Part I
Motivation, Objectives & Introduction

Motivation


TRANSIT TRACTION POWER CABLES: REPLACEMENT GUIDELINES

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JANUARY 14, 2022

- **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.

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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

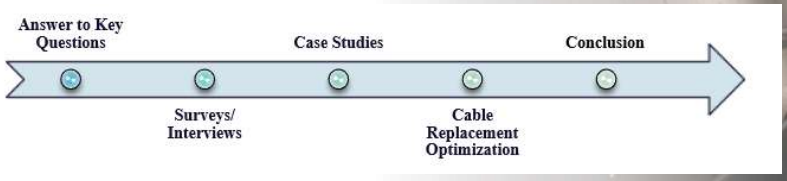
a) Approaches used in transit systems for which there are no monitoring programs and/or testing systems,

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.



Guidebook CONTENT

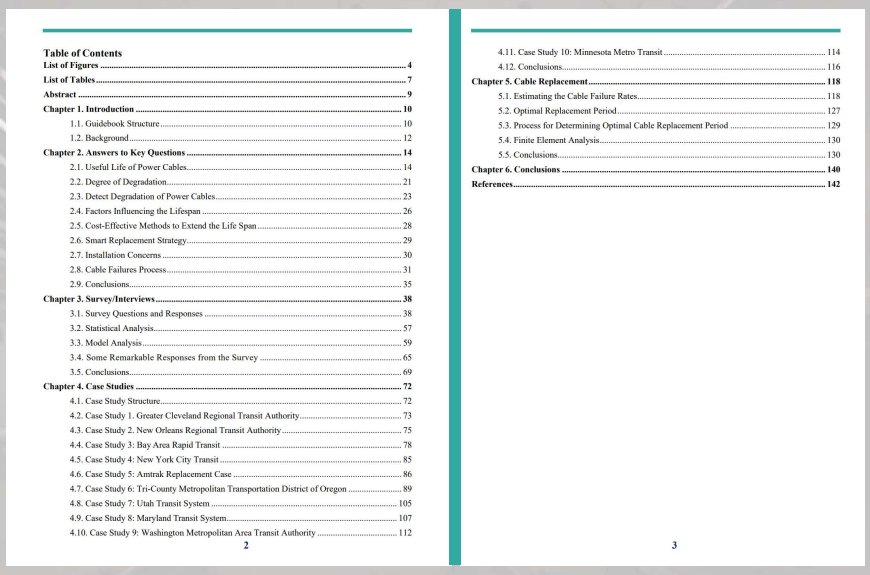


Table of Contents

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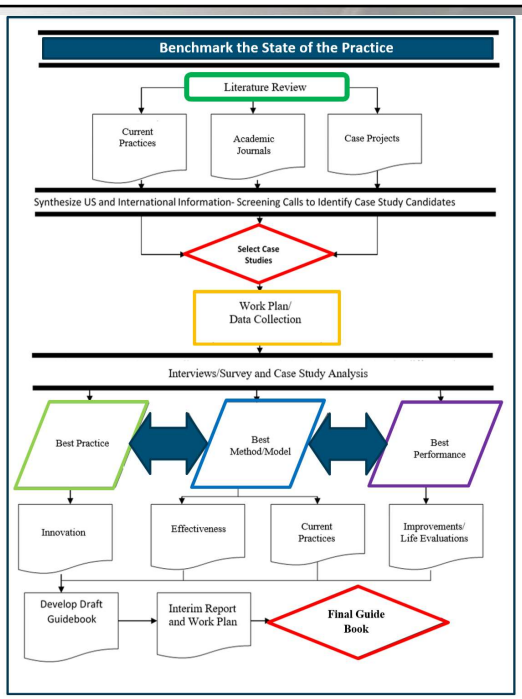
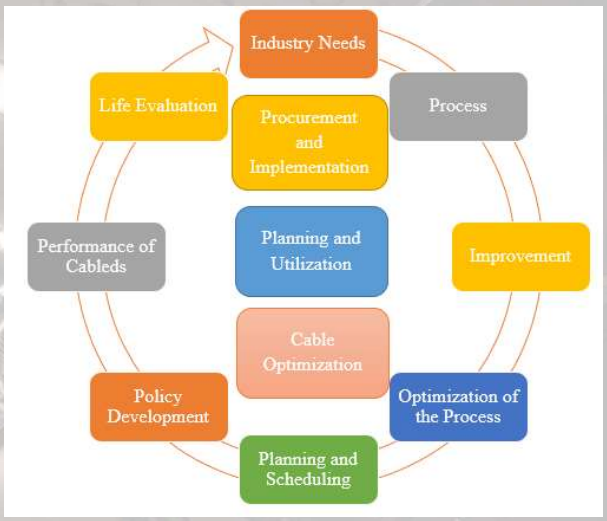
- The work plan to develop the guidebook

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

Key Questions

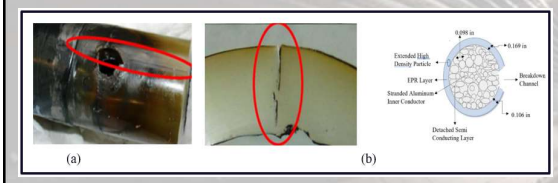
Q1	How is the degree of degradation measured? What is the industry standard for degradation?	*Response:* A measurement unit needs to be determined. For instance, for a mile in a highway, the degree of degradation can be a composite unit that includes the area of potholes, the number of potholes, and the distribution of depth of potholes. Similarly, a measurement unit should be defined for transit power cables.
Q2	What is the lifespan of insulated cables?	
Q3	What are the diagnostic indicators for when insulated cables should be replaced?	*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.
Q4	In what conditions will a cable achieve its maximum useful life?	
Q5	What conditions will accelerate the degradation of a cable?	*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'
Q6	What strategies can be employed to extend the useful life of insulated cables?	

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

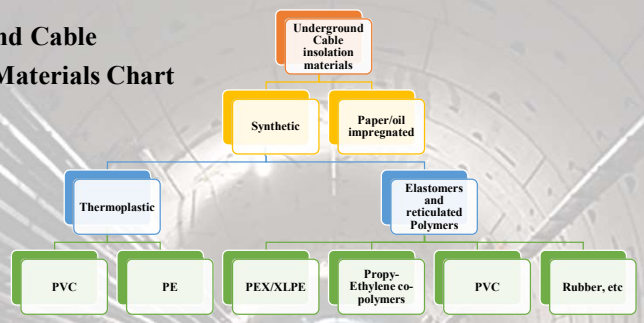
- Major Causes of Failures are classified as:
  - Manufacturing defects,
  - Poor workmanship,
  - External damages,
  - Poor installation,
  - Other aging factors,
  - Thermal, electrical, mechanical, and environmental stresses

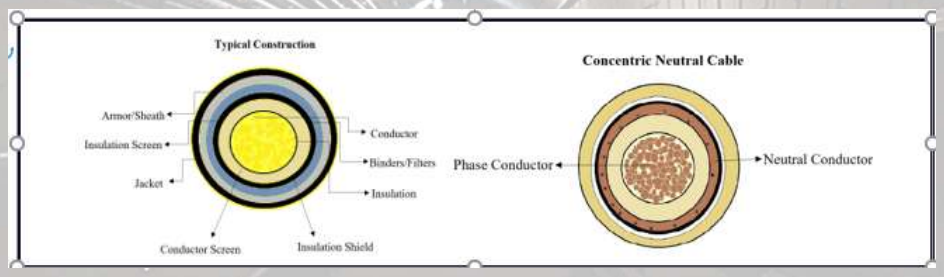


Cable Fault Mechanisms:
(a) Early Failure Caused by Poor Workmanship
(b) Poor Design Resulted in Accelerated Aging
(Aldhuwaian, 2015; Reid 2013)

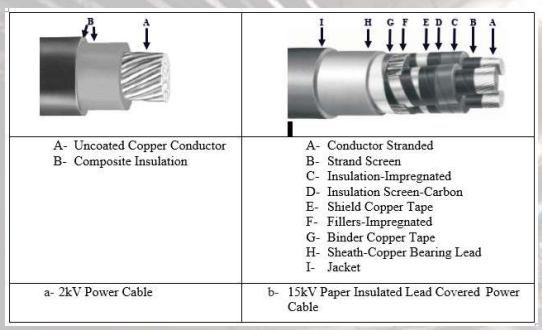
The Proportion of Failures	%
Joint	37
Termination	32
Cable Body	31

Underground Cable Insulation Materials Chart



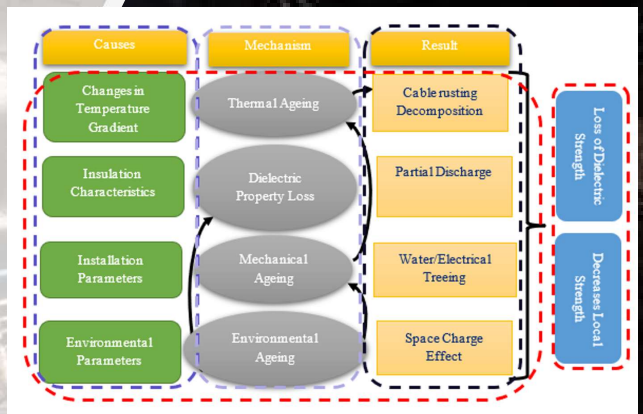


Typical Construction of a Medium Voltage cable
(Levi and Shah, 2018)



A- Uncoated Copper Conductor B- Composite Insulation	A- Conductor Stranded B- Strand Screen C- Insulation-Impregnated D- Insulation Screen-Carbon E- Shield Copper Tape F- Fillers-Impregnated G- Binder Copper Tape H- Sheath-Copper Bearing Lead I- Jacket
a- 2kV Power Cable	b- 15kV Paper Insulated Lead Covered Power Cable

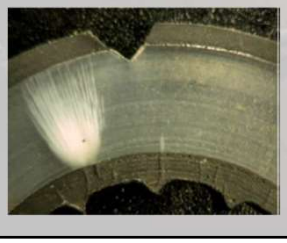
Sample Traction Power Cables Examples

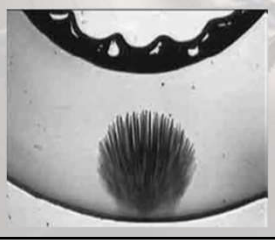


Cable Aging, Mechanisms, and Consequences
(Altamirano et al., 2010; Densley, 2001)

Water Trees

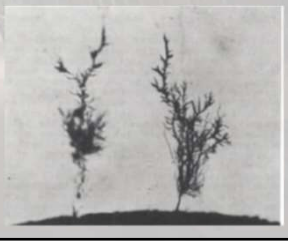
- are tree like patterns,
- branches through the wall of insulation,
- formed from water molecules,
- special dying techniques can make them visible.
- are often found in areas in the cable such as a bend.

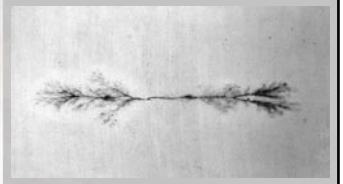




Electrical Treeing

- 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.

Foreign Object in Cable from Installation
(Lanz, 2017)

Corrosion

(Dodds, 2017)

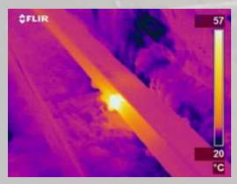
Corrosion is another agent that can cause Cable Rusting decomposition and failure or lead to other defects that can cause failure.

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.



Examples for Overheated Cable (Cloud, 2012)

Installation Errors

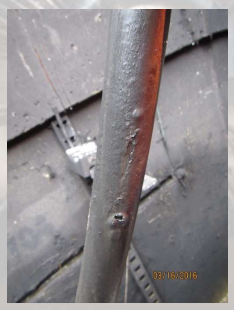
- are the most common agent for cable system faults.
- are never found and it could take years before a fault occurs.
- fault when occurs is accompanied by an arc flash or explosion.

Examples for Common Installation Errors (Lanz, 2017)

Joint Dissection, water Ingress (Neier, 2019)

Examples for Cable Failures

Failures/Splice



Splice

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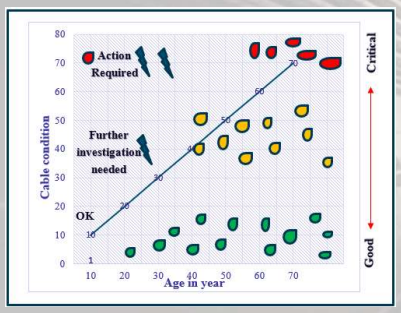
Degree of Degradation

- 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:

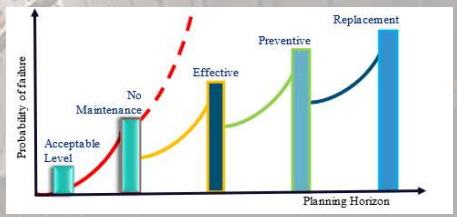
Considering the preexisting contamination and waterbodies when choosing the cables routes.

The water bodies may cause erosion around the cable lines which may lead to leakage into the cables.



Distribution of Cable Condition Versus Life Time (Neier, 2019)

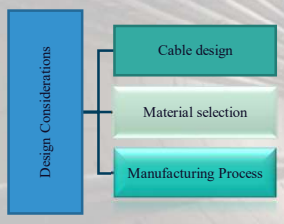
- The Power cables lifetime is generally estimated from the temperature change and associated lifetime reduction. Physical and visual inspections are the most common method of detection of failure (Gouveia, 2014).
- Once degradation occurs in a cable, a failure of some degree will be the next step in 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.



Probability of Failure for Cables (Sachan and Zhou, 2019)

Ageing Factors

- The ageing factors are described in the table.



Cable Design Consideration

Ageing Factor		Ageing Mechanism	Effects
Thermal	High Temperature Cycling Low Temperature	Chemical reaction	Hardening, Softening, Loss of mechanical strength, embrittlement
		Incompatibility of materials	Rotation of cable
		Thermal expansion	Shrinkage, loss of adhesion, separation, delamination at interfaces
		Diffusion	Increase migration of components
		Annual locked-in mechanical stresses	Loss of liquids, gases
		Melting/flow of insulation	Penetration
		Cracking	Shrinkage, loss of adhesion, separation, delamination at interfaces
		Thermal contraction	Loss/ingress of liquid Movement of joints, terminations
Mechanical	Tensile, compressive, shear stresses, fatigue, cyclic bending, vibration	Yielding of materials	Mechanical rupture
		Cracking	Loss of adhesion, separation, delamination at interfaces
		Rupture	Loss/ingress of liquids, gases
Electrical	Voltage -AC, DC, Impulse Current	Partial Discharges	Erosion of insulation
		Electrical Treeing	Partial Discharges
		Water Treeing	Increase losses
		Dielectric losses and capacitance	Increased temperature, thermal ageing thermal runaway
		Overheating	Increase temperature, thermal ageing thermal runaway
Environmental	Water/humidity Liquids/gases Contamination	Dielectric losses and capacitance	Increased temperature, thermal ageing thermal runaway
		Electrical tracking	Increased losses
		Water treeing	Flashover

Ageing Factors (Densley, 2001)

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 experience 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.
Dielectric 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.
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. • A pulse of energy is conducted through a cable from one end and is reflected back when it encounters either the other end of the cable, or a fault in the cable.
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 (LIRA)	• It uses a waveform generator and analyzes electrical test signals to detect changes in the cable insulation's properties.

Cable Inspection Methods (Villaran and Lofara, 2009)

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.*

Useful Life of Power Cables	
Zhou et al. (2017)	The proportion of joint failures, termination failures, and cable body failures was 37%, 32%, and 31%, respectively.
Levi and Shah (2018)	Typical Construction of a Medium Voltage cable.
Aldhuwaian (2015), and Reid (2013).	The underground insulation material Chart.
Altamirano et al. (2010), Densley (2001)	Cable Ageing, Mechanisms, and Consequences.
Terezia (2013)	The growth of water trees in insulation systems play an important role in cable degradation.
Mashikian and Szarkowski (2006)	Water treeing will not inherently cause a fault in the cable. A water tree could even bore through the whole insulation and not cause a fault.
Lanz (2017), Dodds (2017)	Electrical trees are usually visible to the naked eye if found within the insulation.
Laurent (2013)	If a water tree is present, it can hinder the growth of the electrical tree. Another factor is the voltage level when the electrical tree starts to discharge.
Cloud (2012)	Overheating is an agent that can affect underground cable systems.
Lanz (2017)	One of the most common, yet most preventable agents of cable faults are installation errors.
Degree of Degradation	
Chan and Mosleh (2018)	Give the predictive model of the degradation of cable insulation subject to radiation and temperature
Liu (2013)	The virtual degradation rate is determined by fitting experimental data with physics-based equations
Neier (2019)	The method of degradation measurement used permittivity of polymers and the dielectric and mechanical measurements on aged wire insulatio
Szatmari et al. (2015)	The degradation process starts by bio deterioration of the outer polyethylene layer which can be prevented to some extent by cathodic protection against the cable metallic screen's corrosion
Detect Degradation of Power Cables	
Meijer et al. (2015)	Health Monitoring Index (HMI) tool was introduced to assess a cable system's health and to evaluate maintenance strategies.
Sidhu (2010)	Proposed a scheme for early detection of underground cables' faults.
Sachan et al. (2018)	Developed a probabilistic dynamic programming model to find the optimal maintenance policy for power cables using the degradation level and failure distribution of cables.
Orille-Fernandez et al. (2006)	Used artificial intelligence (Artificial Neural Networks ANN) to predict the cable's failure risk.
Kauhaniem et al. (2019)	Proposed that the wave propagation velocity of the cable be determined experimentally to enable locating of the PD faults with increasing accuracy.
Zhang et al. (2018)	Proposes a strategy of utilizing infrared temperature estimation to accurately decide the type and degree of cable defects.
Ocuon et al. (2015)	Presents a thermal examination of an underground power cable systems.
Oclon et al. (2016)	Application of momentum-type Particle Swarm Optimization for the thermal performance optimization of the underground power cable systems.
Kruiizinga (2017)	The replacement of grid sections only takes place after repeated outages in the same section, as there are no methods available to perform diagnosis on LV grids.
Nemati et al. (2019)	The effects of control cables' reparability characteristic on failure rate estimation is displayed.

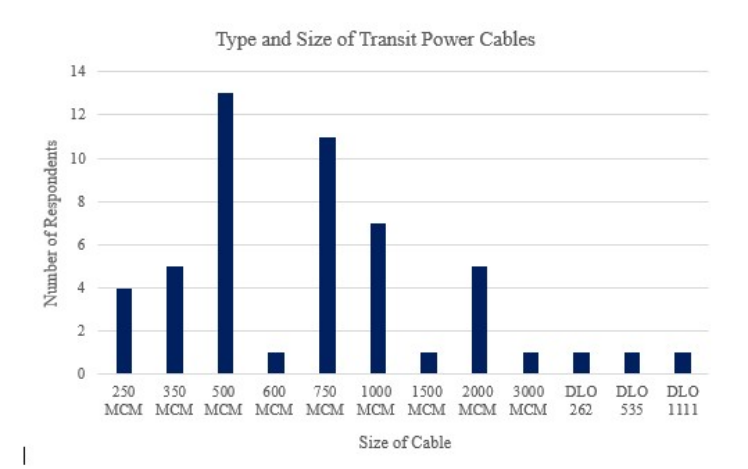
Part III
Survey & Interviews

Data collection process was carried out with transit agencies and practitioners in the industry with survey study and case studies.

Region	System Size /Miles	-Old-New/~Years	System Installation	System Length (mile)	DC	AC
Mid-West	Small	Very Old/70+	1950s	36	x	
Northeast	Very Large	New/2000	2005	625	x	
	Large/30+	New	2009	30	x	x
Ohio Valley	Large/40+	very old	1900s	600	x	
West	Medium	old	1985	42.2	x	
The-South	large/30+	old/60+	1960s	33.4	x	x
California	Large	Old/60+	1970s	125	x	x
Mid-Atlantic	Medium/+	Old/50+	1973	14		x
Ohio Valley	Large/38	Old/60+	1955	38	x	
The-South	Large/33	Very Old/1893	1893	33	x	
Northeast	Medium/30	Very old/105	1900s	30	x	
West	Very Large/200	New to Old/5-30	2000-2015	200/50	x	
Ohio Valley	Very Large/220	Old	1920s	220	x	
Northeast	Very Large/245	Old/1904	1904	245	x	
Ohio Valley	Ver large/200+	Old and New	1900-2000	225	x	x
South	Medium/22.7	New/5 years	2014	22.7	x	
North west	Large/62	Old/20	2000s	62	x	
Northeast	Large/34	Old/49	1989/1969	34/15	x	
Mid-Atlantic	large	very old	1920s	125	x	x

	Location	Authority	Contact Info	Contact Person	e-mail
1.	North Little Rock, AR	Rock Region Metro			
2.	Tuscon, AZ	City of Tuscon Transit Agency			
3.	Phoenix, AZ	Valley Metro			
4.	Los Angelas, CA	Los Angeles County Metropolitan Transportation			
5.	San Diego, CA	North County Transit District			
6.	Sacramento, CA	Sacramento Regional Transit District			
7.	San Diego, CA	San Diego Metropolitan Transit System			
8.	San Francisco, CA	San Francisco Municipal Transportation Agency			
9.	San Francisco, CA	San Francisco Bay Area Rapid Transit District			
10.	Santa Clara, CA	Santa Clara Valley Transportation Authority			
11.	San Carlos, CA	Caltrain			
12.	Oakland, CA	WSP			
13.	Oakland, CA	Bart			
14.	San Francisco, CA	PGH Wong Engineering			
15.	San Francisco, CA	PGH Wong Engineering			
16.	San Francisco, CA	PGH Wong Engineering			
17.	Santa Clara, CA	VTA			
18.	Los Angeles, CA	LAMetro			
19.	Denver, CO	Denver Regional Transportation District			
20.	New Milford, CT	Neeltran			
21.	Washington D.C.	Washington Metropolitan Area Transit Authority (WMATA)			
22.	Washington, D.C	AMTRAK			
23.	Washington D.C.	Power at The Burns Group			
24.	Miami, FL	Miami-Dade Transit			

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



- Type and Size of Transit Power Cables Used in the System.

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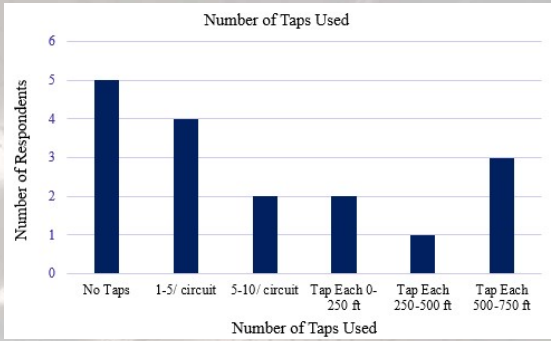
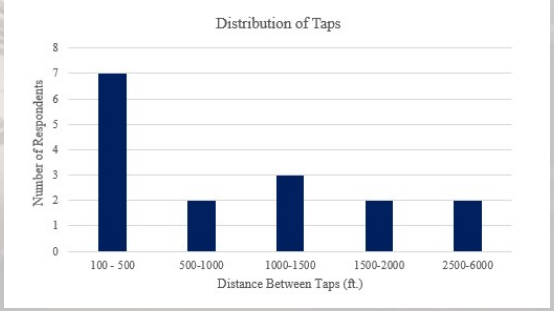
How many taps per hundred feet are in your cables? Mmaximum number of taps allowed per circuit?





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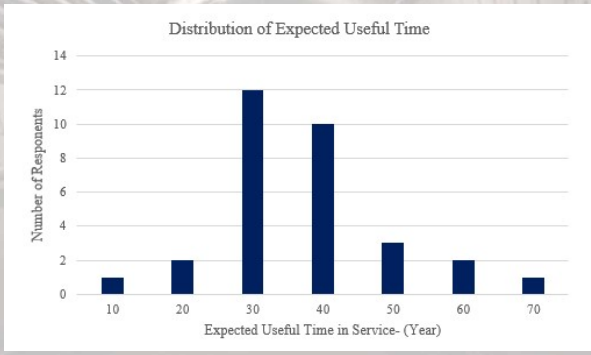
3. What is the expected useful lifetime of cables that you use? Do you follow any practices to increase the useful life of the cables?

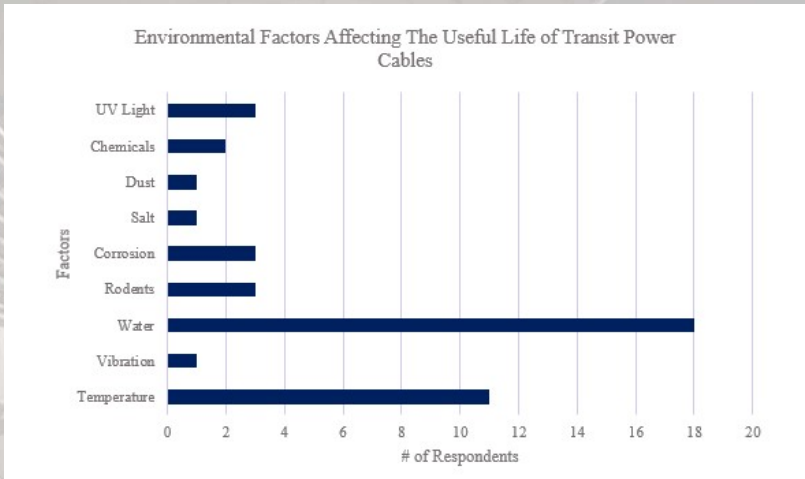
Steps to maximize cable life:
1. Design to minimize heating of cables due to overload
2. Design to minimize damage during installation (large bend radii, pull boxes less than 500' apart)
3. Ensure cables and taps are kept dry



Distribution of Expected Useful Life

32

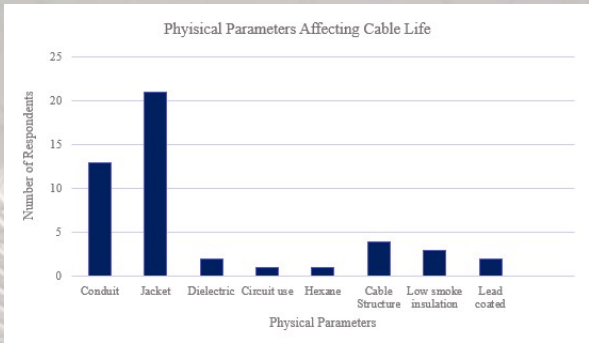
4. What are the environmental factors such as temperature, animals (birds, rodents), water, above or below the water level, etc. affecting the useful life of transit power cables?



Environmental Factors

33

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



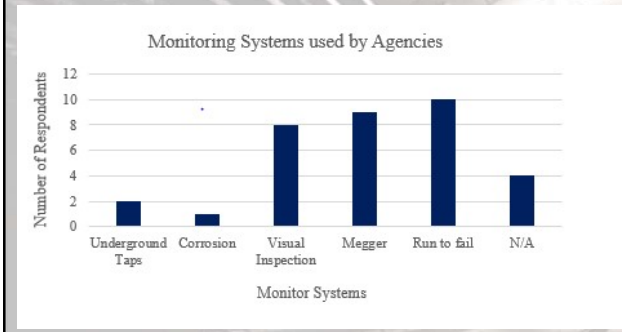
Physical Parameters Affecting the Life of Transit Power Cables

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:

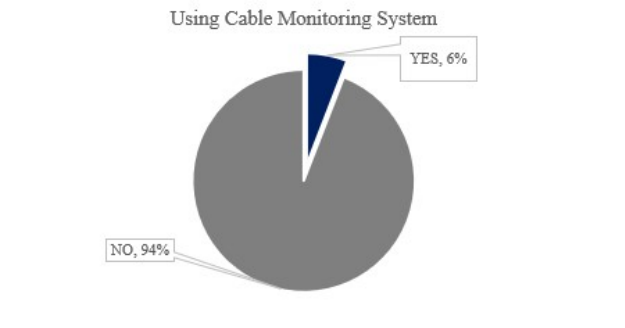
- "Cable insulation/jacket designed for wet locations."
- "Insulation rated for well above system voltage to handle transient surges."
- "Properly designed duct bank (drainage, depth) to maintain dry and cool cables."
- "Proper separation and support of cables in manholes."
- "Design duct bank for minimal cable-pulling stress (broad sweeps, frequent pull boxes)."

34

6- How do you determine the degree of degradation of insulated cables? Do you have cable monitoring systems?



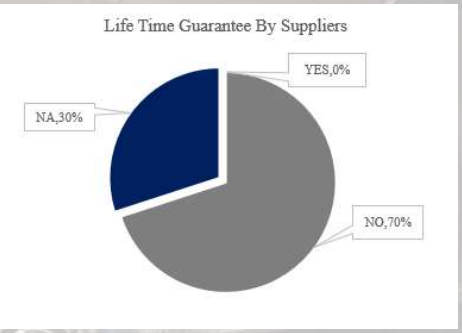
Degree of degradation monitoring systems



Cable monitoring system usage

35

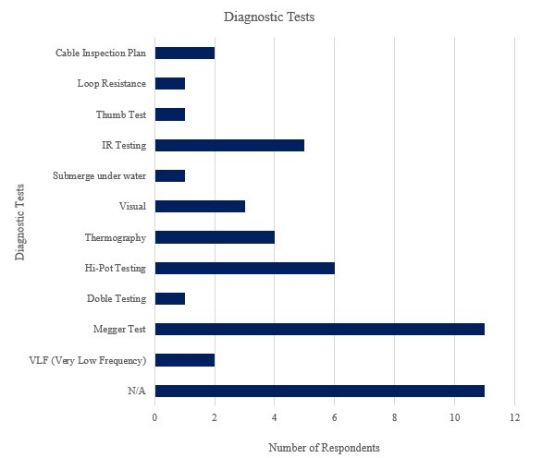
7- Is there a lifetime guarantee by the suppliers? Are there any maintenance, testing, replacement schedules suggested by the supplier?



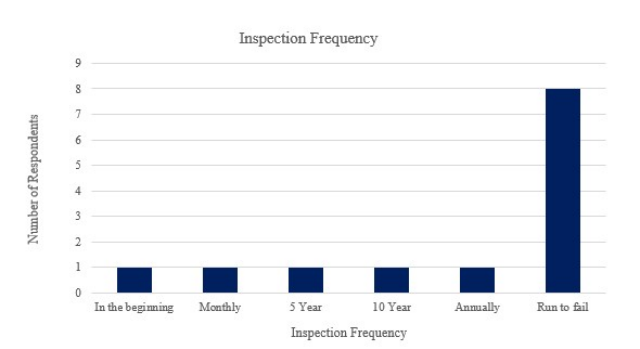
Lifetime Guarantee

36

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



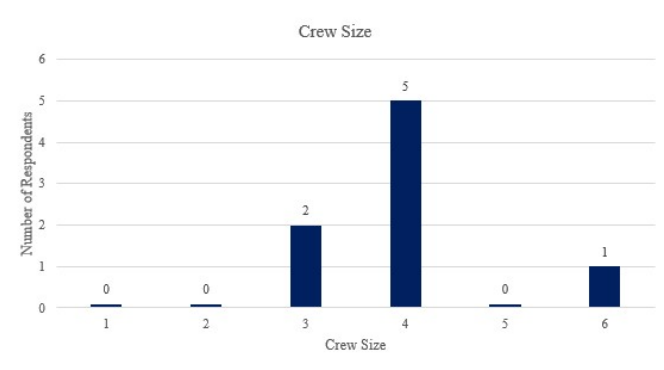
Diagnostic Test Types



Inspection Frequency

37

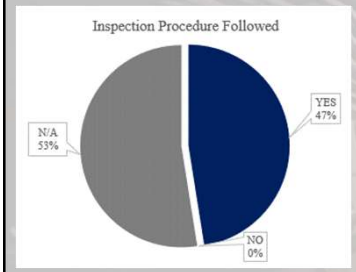
9- What is the crew size?



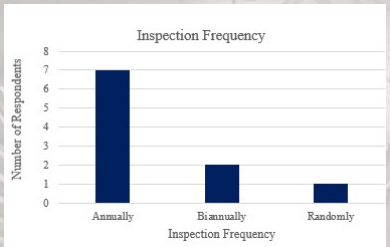
Crew Size

38

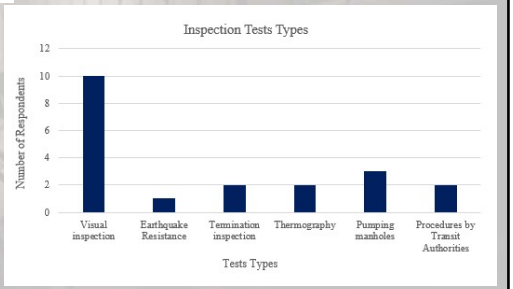
10. Do you practice any cable inspection and maintenance procedures? If so, please describe your procedures including intervals and types.



Cable inspection and maintenance procedures

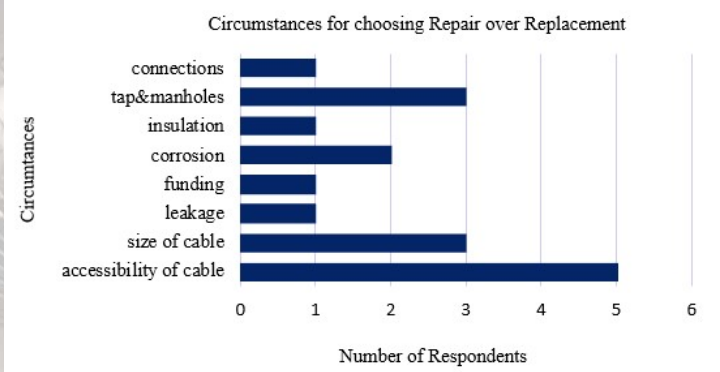


Procedure intervals



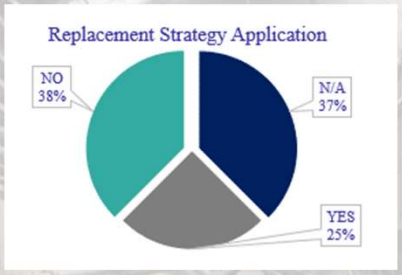
Types of Tests

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

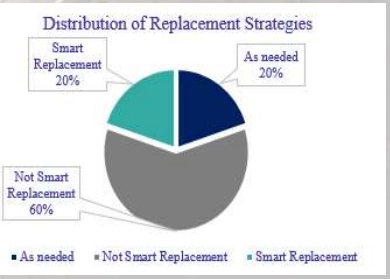


Circumstances for choosing Repair over Replacement

12- Is there any replacement strategy including "Smart Replacement Strategy" that you are implementing for insulated cables?



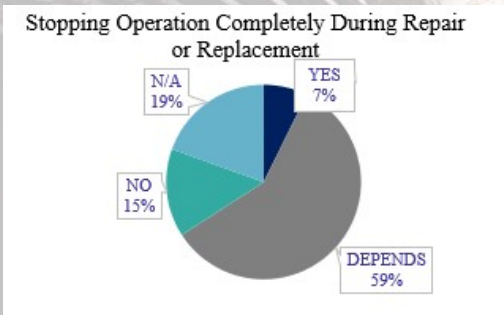
Replacement Strategy Application



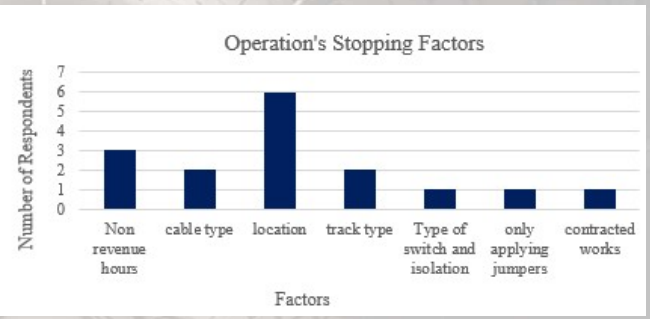
Distribution of Replacement Strategies

41

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



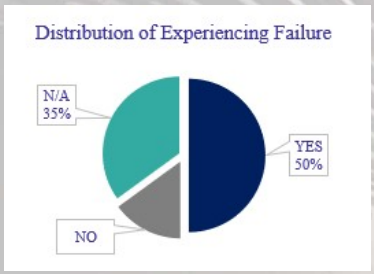
Stopping Operation



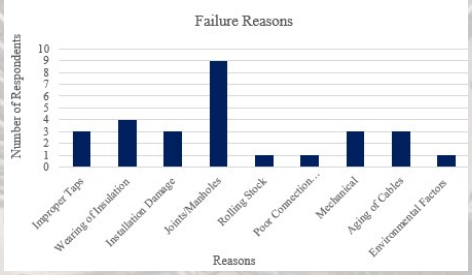
Distribution of factors stopping the operations

42

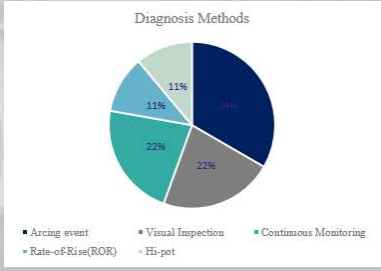
14- Were there any failures being experienced by your agency? Are the reasons behind the failures known? How do you diagnose failures?



Distribution of Experiencing Failure



Failure Reasons

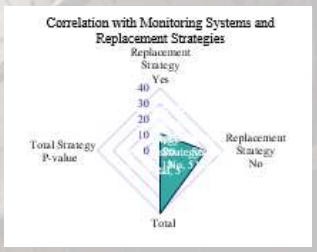


Diagnosis methods

Statistical Analysis

Correlation Results for Monitoring Systems and Replacement Strategies

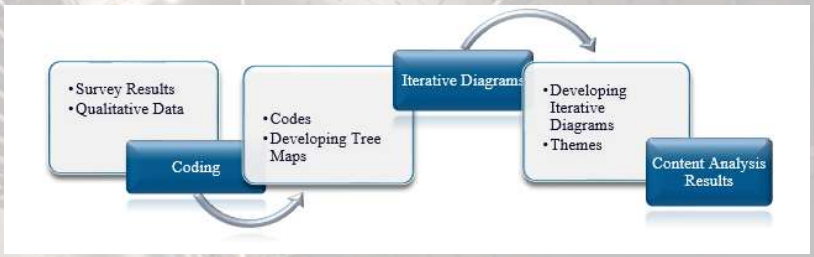
		Replacement Strategy		Total	P-value
		Yes	No		
Monitoring System	Yes	0	5	5	0.18
	No	11	24	35	
Total		11	29	40	



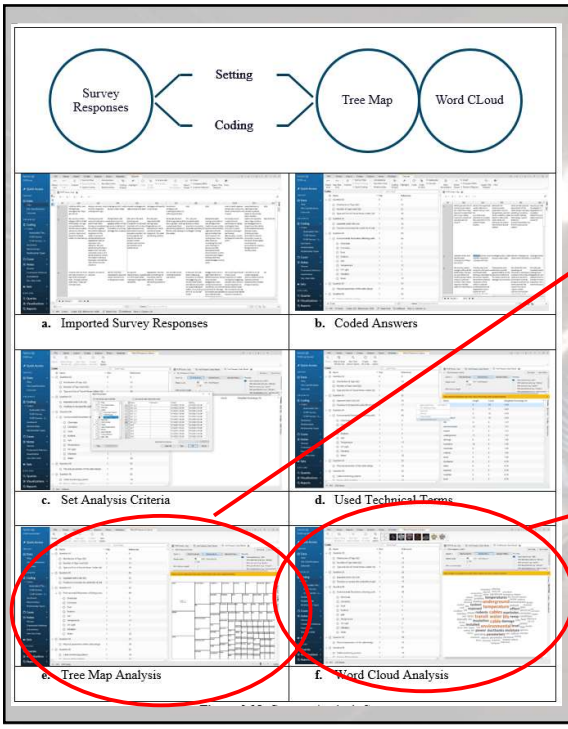
- the Fisher's Exact test revealed that using a cable replacement strategy did not significantly change by using a monitoring system (p>0.05). The significance level (p) was found as 0.18. Out of the 35 responders who do not have a cable monitoring system

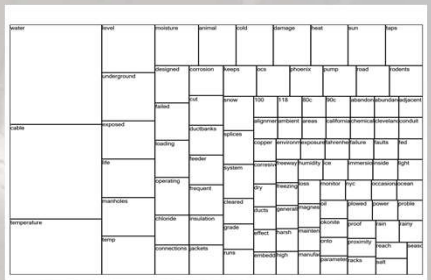
Content Analysis

- 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





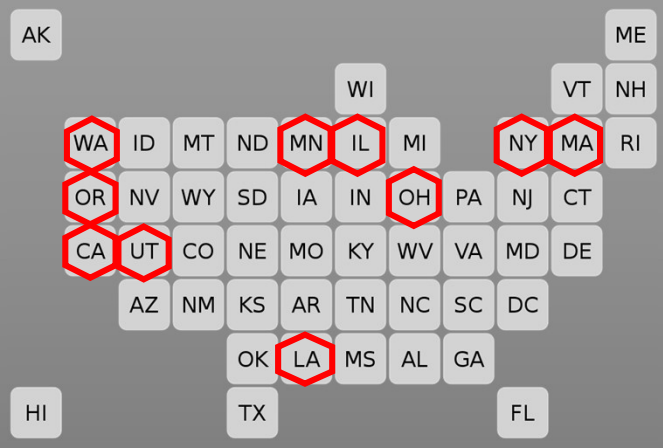
Sample for Q4 Environmental Factors Affecting Cables

A Summary for Survey Answers

#	Questions	Most Common Answers
1	Data collection process	Participants were selected from various locations to define their properties.
2	Type and size of transit power cables	Sizes range from 250 MCM to 3000 MCM, with the most popular sizes being 500 MCM, 750 MCM, and 1000 MCM.
	How many taps per hundred feet	From no taps to 10 taps per circuit.
	Maximum number of taps	Spacing between taps is 100 ft to 500 ft.
3	Expected useful lifetime of cables	30 to 40
	Practices to increase the useful life	Design considerations include minimizing the heating of cables due to overload.
4	Environmental parameters affecting the useful life of transit power cables	Two stand-out factors are water and temperature.
5	Physical parameters of the cable design	Jacketing and conduit insulation.
6	Determine the degree of degradation	Include the Megger test, visual inspection, and a 'Run to Fail' method.
	Cable monitoring systems	Only 6% of the participants have stated that they have a monitoring system.
7	A lifetime guaranteed by the suppliers	There is no lifetime guarantee by suppliers.
	Maintenance, testing, replacement schedules suggested by the supplier	Suppliers provide support to agencies in case any problems occur.
8	Diagnostic tests carried out on transit cables	Megger, Hi-Pot, and IR Testing are the most regularly implemented.
	How often do you need to run these tests	Agencies generally conduct diagnostic tests when a failure occurs.
9	Costs to run each type of test including the number of operators and time length	Crew comprises three to four people.
	Stop operations	Power outages, service interruptions, and crews kept from performing other vital tasks.
	Does any of the tests have potential to damag	Tests always have potential to damage the cables.
10	Cable inspection and maintenance procedures	Over half of the respondents to question 10 indicated that they did not have established inspection and maintenance procedures.
	How often they conduct cable inspection and maintenance	Annually
	Types of inspection tests	Visual inspection

#	Questions	Most Common Answers
11	What types of repairs are made	Limited to splicing the cables.
	Under what circumstances, choose repairing the cable in comparison to replacing	Accessibility of cable for repair.
	Diagnostics indicators for replacing insulated cables	When green cable corrosion is found floating in water filled manholes during an inspection test, or when a ground short is detected during insulated cable inspections.
	General costs and durations of repair and replacement	Varies depending on the size and location of the fault in the cables, as well as the number of conductors per circuit.
12	Is there any replacement strategy including "Smart Replacement Strategy" .	Mostly no replacement strategy is applied and if apllied Less than half of the strategies employed qualified as "smart".
13	Do you have to stop operations completely during repair and replacement	Operation is completely or partially stopped during repairs and replacement. It depends mainly on the location of work.
14	Failures being experienced	Half of all respondents reported experiencing failure.
	Are reasons behind the failures known?	The most common failures occur at manholes and joints due to water intrusion.
	How do they diagnose failures?	• Arcing event • Visual Inspection • Continuous Monitoring • Rate-of-Rise (ROR) • Hi-pot

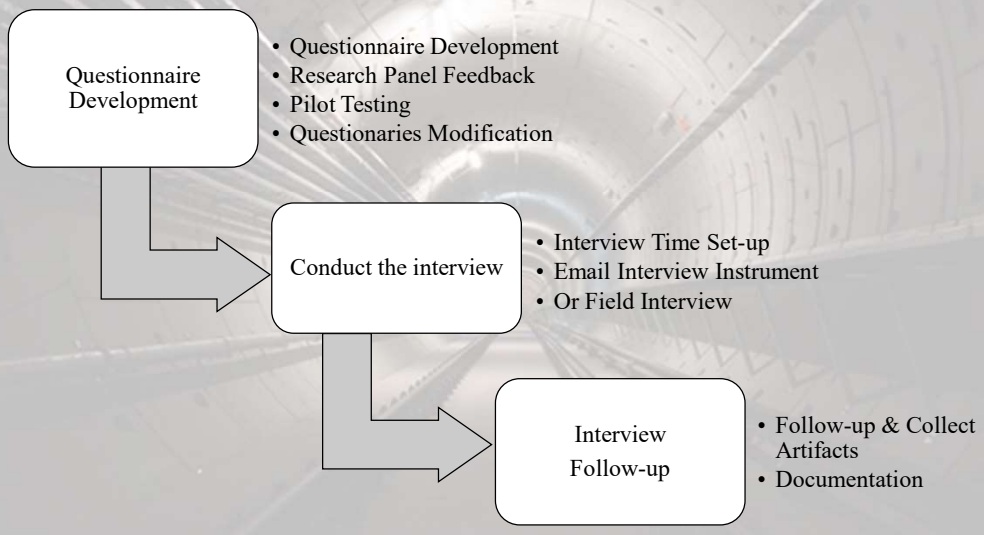
Part IV.
Case Studies



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



Case Study 1: Greater Cleveland Regional Transit Authority

Table 4.1. Greater Cleveland Regional Transit Authority

	Length (miles)	*Age (years)*	*Electrification system (voltage, current type, contact system)*
Tram (streetcar, trolley)			
Light rail	17	44 for B&G and 23 for Waterfront	Overhead simple catenary system (OCS). 600v DC
Rapid transit (metro, subway, underground)	20	Approx. 50	Overhead complex catenary system (OCS). 600v DC

Concept		Current Practice
Quick view		A weekly riding visual inspection is performed in which maintenance workers observe the OCS for defects. A 6-month walking inspection is performed in the fall and spring where maintenance workers can work at a slower pace visually inspecting for defects from the ground. Defects noted during either inspection are then inspected hand on and repaired as soon as possible by a secondary crew. There is also a hands-on inspection that is performed on a piece or work equipment with an elevated platform so the crews can physically touch and inspect the OCS. Bolted connections and overhead equipment such as section insulators, pullovers, splices, and feeder cables are inspected during this annual preventative maintenance task. Manhole inspections are performed every 6 months as well and routinely check manholes in between inspections to pump potential water from the holes. The manholes are one of the biggest issues because of their locations. Many are located in or near parking lots and roadways and we have seen issues with roadway salt during winter months affecting the life of the cables.
Summary	Degree of Degradation	They determine the degradation and condition of our feeder cable through routine maintenance. They inspect the overall appearance of the cable as well as its bolted electrical connections. They look for signs of weathering, fire or heat damage and cuts/tears in the jacket which may have been caused by accidents of damage from falling tree limbs. These types of inspections have various intervals ranging from every six months for routing visual inspections to a more in-depth hands-on inspection on an annual basis. In the manholes mentioned above, they look for indications of failure by heat in the manhole, steam coming from potential water. They look at the water to observe its color (green could indicate failure) and observe the cable for degradation.
	Diagnostic Indicators	They do not perform diagnostic testing on the feeder cable. The recommendation from APTA is specific for cables in conduit, duct back and troughs which may be susceptible to rodents or degradation due to moisture and electrolysis. The insulation-resistance testing is also only recommended when the integrity of the cable is suspect. Current inspection and maintenance schedule is adequate to inspect the feeder cable in a timely manner to observe any potential issues and damage to the existing cable on our property.

Cost Determination

Category	Parameters
Failure or unplanned interruption cost	Average hourly power consumption (L_h)
	Average unplanned interruption time in hours (t_r)
	Power Outage Costs (d_h)
	Time-dependent power outage cost (b_h)
	Average failure costs (C_F)
Maintenance cost	The average cost of diagnostic tests and inspection is negligible in compared to repair and replacement cost
	Average maintenance cost for cable (C_M)
Repair cost	The average repair cost of single failure is
	Average CM repair (C_{RCM})
	Average PM repair (C_{RPM})
Cost of replacement	Cost of new cable (C_{cable})
	Cost of installation (C_{inst})
	Replacement cost of cable (C_{RP})

What are the general costs and durations of repair and replacement?

4 responses

- Vary
- If can be done in house or need a contractor. Could be days or a week or more .Cost driven up by not having in stock,and of 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?

3 responses

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

**Survey Responses*

Case Study 2: New Orleans Regional Transit Authority

Table 4.3. New Orleans Regional Transit Authority

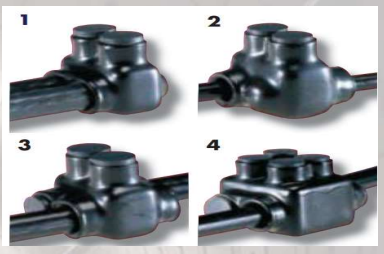
	Length (miles)	*Age (years)*	*Electrification system (voltage, current type, contact system)*
Tram (streetcar, trolley)	625	20	DC
Light rail			
Rapid transit (metro, subway, underground)			
Commuter rail			
Other (Please state the type)			

Concept		Current Practice
Quick view		The traction power personnel performs complex and specialized troubleshooting, preventative and corrective maintenance, and overhauls of traction power substation and overhead contact system and their associated sub-systems. The traction power maintenance team is responsible for assuring that all equipment is working and aligned properly to prevent damage to system and rail vehicles. They will also provide emergency response and will be called upon to provide support for other areas in regard to light rail service, special events, streetcar, and public safety and service.
Summary	Degree of Degradation	There is no procedure to determine degree of degradation. The cables are checked physically in a certain period. Majority of the cables are under the water and that makes such determination procedure difficult.
	Diagnostic Indicators	They are checking the substations. If there is a heat increase in the substation, this is an indicator for the maintenance crew. They do not have time to stop the operation for regular check-up. Therefore, they check the substation regularly. They have visual inspection manholes, and taps.
	Effecting Factors	For overheads, trees are the main environmental factors for them. They create some problems in case of extreme weather conditions. The other main problem is that the city is under the water, which makes cables under the water in their service life. Over the time, it penetrates.
	Replacement Strategies	They created the cable jacket itself to increase the life cycle as seen in Figure 4.2. They designed their own taps that helped them to prevent water from the taps. They placed the taps in PVC sealed cages. They use a certain type of taps for aluminum cables as seen in Figure 4.3. Figure 4.4 shows the tap connectors for aluminum cables and Figure 4.5 shows the tap connectors used in New Orleans Agency. Table 4.4 presents Problems and Outcomes
	Smart Replacement Strategy	They do not currently have a smart replacement strategy

Cables used in New Orleans Agency

New Orleans Regional Transit Authority

Taps Created by the Agency



Tap connectors for aluminum cables

Tap connectors used in the Agency

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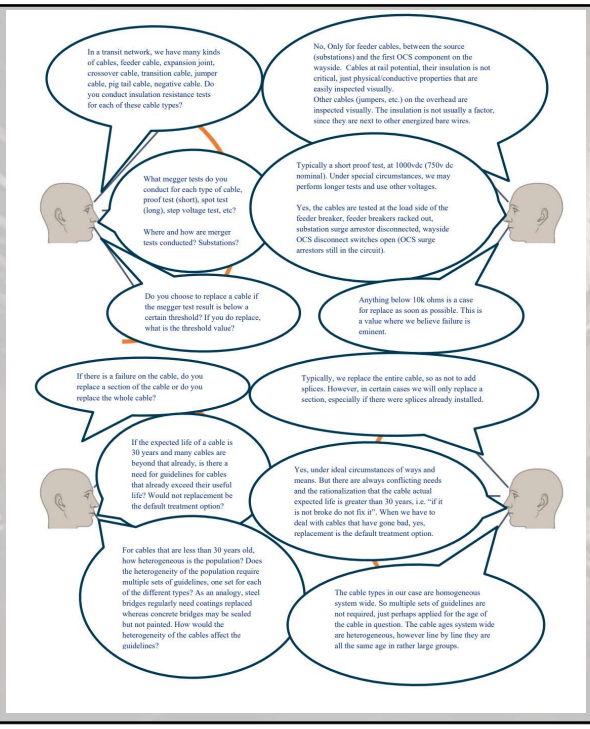
Case Study 6: Tri-County Metropolitan Transportation District of Oregon

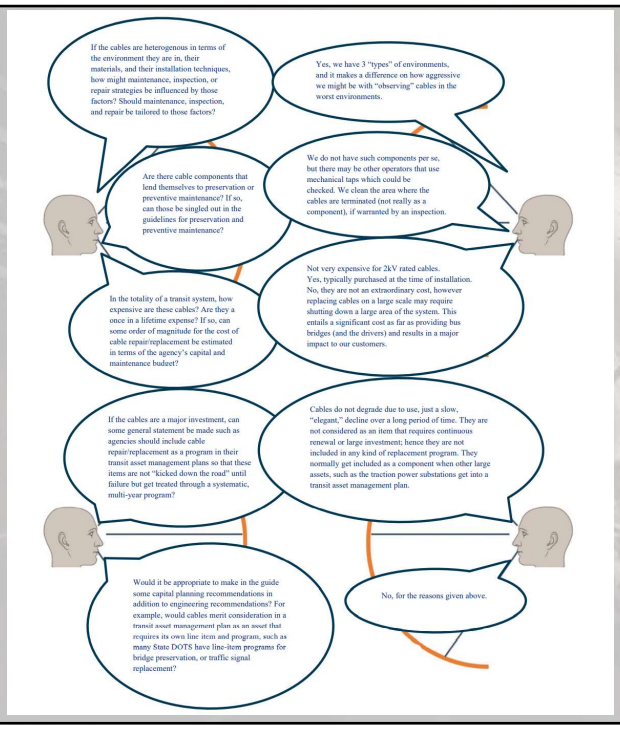
Table 4.18. Tri-County Metropolitan Transportation District of Oregon

	Length (miles)	*Age (years)*	*Electrification system (voltage, current type, contact system)*
Tram (streetcar, trolley)			
Light rail	62	20	750 VDC OCS
Rapid transit (metro, subway, underground)			
Commuter rail			
Other (Please state the type)			

Concept		Current Practice
Quick view		They typically do a hard visual inspection on cables during the meggering process. Now they do a visual inspection on feeder cables inside the substation during annual track feeder breaker inspections.
Summary	Degree of Degradation	Degradation has not been something they have been able to quantify. No cable monitoring systems in use.
	Diagnostic Indicators	In the past, they had been measuring insulation resistance by meggering, but results were varied, and failures occurred on supposedly good cables, so currently they are in a "run to fail" mode.
	Effecting Factors	Splices and taps subjected to seasonal water immersion in underground vaults
	Replacement Strategies	There is no replacement strategy. Only during the actual replacement work, which they try to do during non-revenue hours or in combination with other work outages. The failed cable can be taken out of service and operations can resume.
	Smart Replacement Strategy	Not existing
Review and Update		Considerations in practice: Cable life, Cable failure modes, Installation considerations, Environmental issues, Manufacturability, and Cost
Examples:		In Figure 4.9, a sample physical and animal damages are presented. Figure 4.10. presents Megger Test Procedure. Figures 4.11 and 4.12 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 4.13 to 4.16, construction practices are presented. In Figures 4.17 and 4.18, cable failures are presented. Figure 4.19 presents Rail to Ground Voltage Monitor and Figure 4.20 presents Splice Details. Figure 4.21 presents Electrification Details.



Agency Responses to the Critical Problems I



Agency Responses to the Critical Problems II

Construction Practices

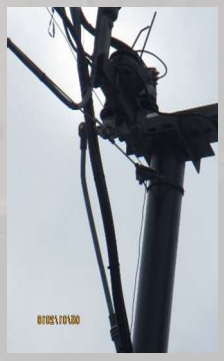
Cable Samples






Cable Samples



Overhead Cable Connection Samples

Cable Damages

Physical Cable Damage

Animal Damage

Damaged Cable Sample

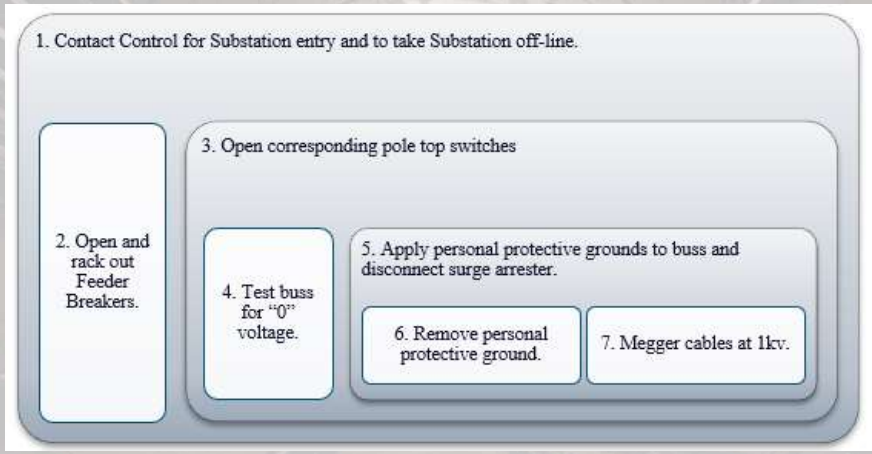
Failure and Repair Samples

Experienced Cable Failure Examples



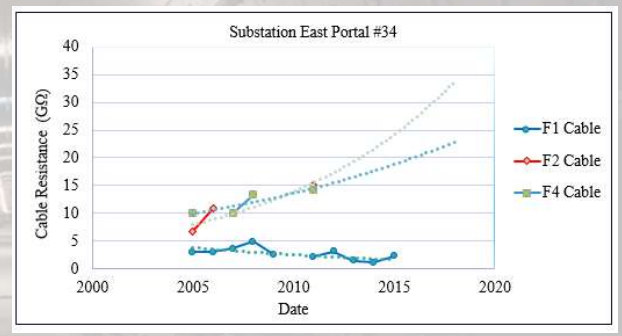



Megger Test



Sunset #23 Cable Megger Log

Feeder Cable Megger Log				
Sunset #23				
Date	F1 Cables (Ω)	F2 Cables (Ω)	F3 Cables (Ω)	F4 Cables (Ω)
8/30/2006	6G	7.5G	N/A	N/A
7/6/2007	8.1G	9.5G	N/A	N/A
7/23/2008	7.6G	8.9G	N/A	N/A
7/10/2009	7.2G	9.2G	N/A	N/A
10/31/2011	2.12G	5.4G	N/A	N/A
10/18/2012	1.8G	6.5G	N/A	N/A
10/28/2013	2.6G	7.1G	N/A	N/A
10/9/2014	1.42G	5.8G	N/A	N/A
4/25/2017	2.2G	6.0G	N/A	N/A
4/28/2018	3.76G	6.5G	N/A	N/A



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Hawthorn Farm #34 Cable Megger Log

Feeder Cable Megger Log				
Substation East Portal #34				
Date	F1 Cables (Ω)	F2 Cables (Ω)	F3 Cables (Ω)	F4 Cables (Ω)
12/28/2005	3.08G	P 6.75G	N/A	P 10.1G
10/10/2006	3.04G	P 10.9G	N/A	
9/12/2007	3.70G			P 10.0G
9/29/2008	4.96G		N/A	P 13.4G
9/22/2009	2.58G			
7/11/2011	2.18G	(2min) 15.0G	N/A	(2min) 14.3G
7/2/2012	3.16G	2 min		
7/1/2013	1.47G			
7/1/2014	1.13G			
7/1/2015	2.26G			
1/11/2018	2.45G			

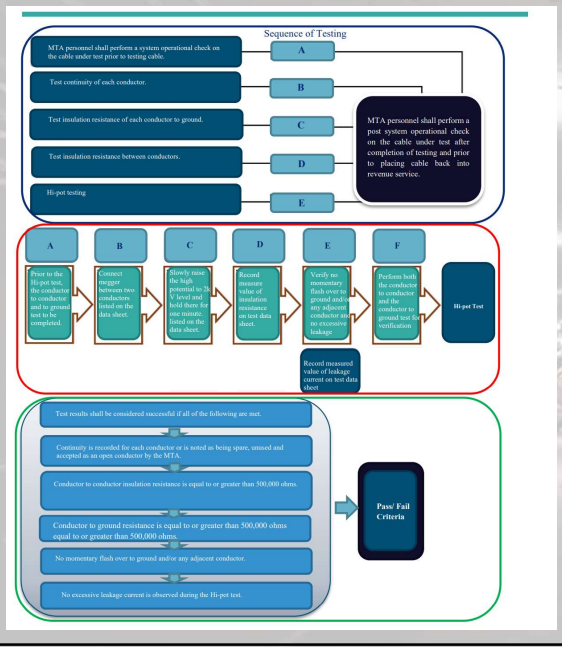
Case Study 8: Maryland Transit System

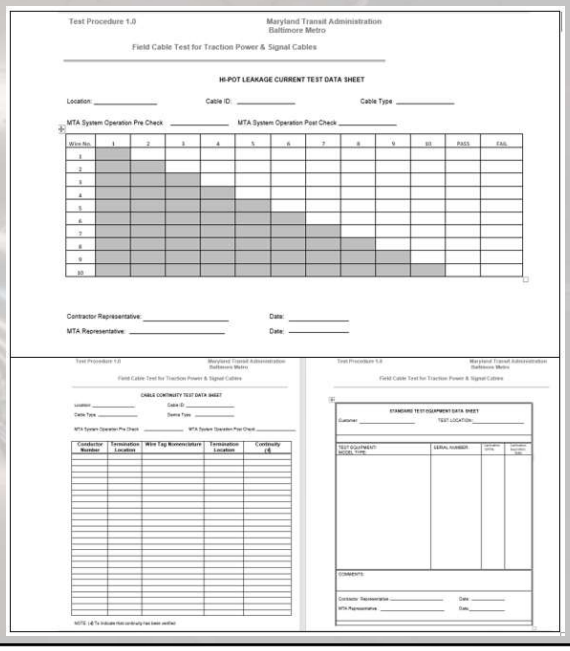
Table 4.26. Maryland Transit System

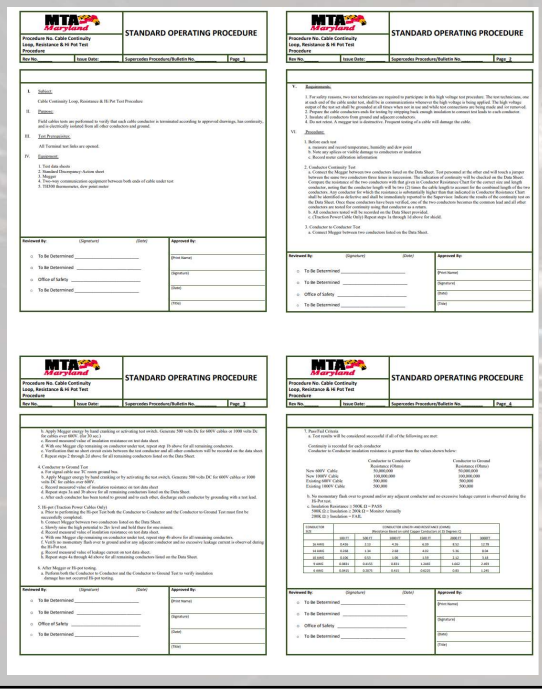
	Length (miles)	*Age (years)*	*Electrification system (voltage, current type, contact system)*
Tram (streetcar, trolley)			
Light rail	34	29	750Vdc, Catenary
Rapid transit (metro, subway, underground)	15	49	750Vdc, Third Rail
Commuter rail			
Other (Please state the type)			

Concept		Current Practice
Quick view		They use 1000 MCM traction power cables, running 4 (four) 1000 MCM cables to each third rail section per breaker. We use no taps, we run directly to the third rail and jumper each section of third rail. See Figure 4.29 MTA sketch for detail for Power Supply Configuration. In Figure 4.30, MTA Testing Procedure Details are given. In Figure 4.31, Maryland Testing Procedure is provided. In Figure 4.32, MTA Standard Operating Procedure Data Sheets are given.
		All failures have resulted from wearing through the outer insulation due to vibration and expansion/ contraction. The failure diagnoses itself via a arcing event, tripped breaker, fire etc.
Summary	Degree of Degradation	Twenty years and every ten (10) years they perform cable testing as mandated by the power supplier. They perform physical inspection of the cables to prevent accelerated physical degradation due to expansion and vibration. They add additional jacketing in areas known to have excessive wear the aerial structures where the cables must have expansion and rub the side of the concrete structure.
	Diagnostic Indicators	They perform hi-pot for new cables. Cables are replaced when large sections are damaged and can no longer be repaired due to many issues. Utilizing connections reduces connection issues in the field. These cables are all special procurements so prices change based on industry costs.
	Effecting Factors	The crew sets up their cable test set at a location determined by the parameters of the cable to be tested. As the test set requires 600 volts DC to operate, the location is usually in a substation or on the right of way where there is a 600 volt DC source.
	Replacement Strategies / Smart Replacement Strategy	They do not have a cable monitoring system in place. We do a physical inspection of the cable and initiate a 10-year test plan. They repair a cable if that option is available. Cost or repair or replace is based on length, type of install, access, thus every cable presents a different cost. Mandated cable testing costs 4.4M to test all signal and traction power cables system wide at Metro. Light Rail will cost approximately the same amount. All testing must occur after revenue increasing the total costs. No smart replacement strategy was applied.

MTA Testing Procedure Details







MTA Standard Operating Procedure Data Sheet

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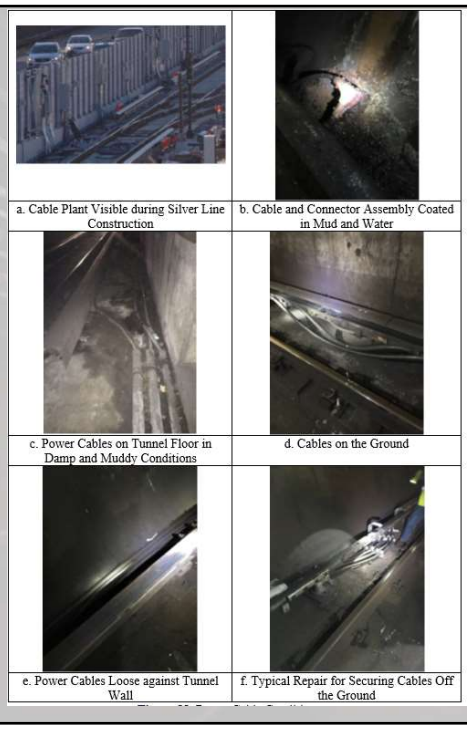
Case Study 9: Washington Metropolitan Area Transit Authority

Findings	Required Actions
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.	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 TRPM; 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 IRCM; engineering services provided by PWRS; and lock-out/tag-out procedures implemented by the ROCC and MOC.
WMATA ROCC and MOC personnel are not sufficiently proactive in managing TPE concerns during emergencies.	Emergency Removal and Restoration of Third Rail Power Mainline 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.
Insufficient resources are available to support the testing, inspection, and maintenance of WMATA's TPE system.	WMATA must evaluate options for using contractors to complete its TPE system corrective maintenance backlog and outstanding preventive maintenance requirements in the near-term and implement results.
Traction Power Cables	Traction power cables are often loose on the ground, subjecting them to contamination, vibration, and damage from movement.
Negative Return System	WMATA does not implement a consistent program regarding its negative return system's testing, inspection, and maintenance.
Insulation Resistance	WMATA does not currently test cables to ensure insulation resistance.
Examples	Power Cable conditions and various stages are presented in Figure 4.33.



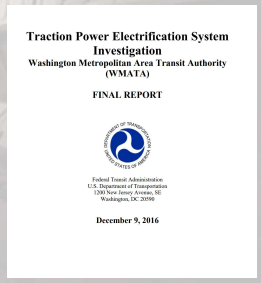
a. Cable Plant Visible during Silver Line Construction | b. Cable and Connector Assembly Coated in Mud and Water

c. Power Cables on Tunnel Floor in Damp and Muddy Conditions | d. Cables on the Ground

e. Power Cables Loose against Tunnel Wall | f. Typical Repair for Securing Cables Off the Ground

Cable Conditions

Traction Power Electrification System Investigation



Traction Power Electrification System Investigation
Washington Metropolitan Area Transit Authority (WMATA)

FINAL REPORT

Federal Transit Administration
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

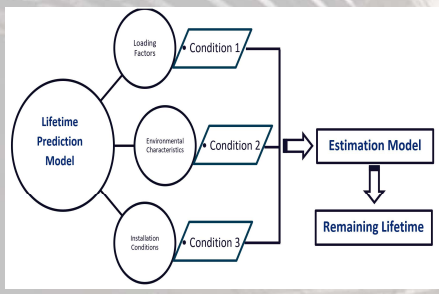
December 9, 2016

Case Study		1	2	3	4	5	6	7	8	9	10
Maintenance Schedule	Heat increase observed					•					
	Visual inspections	•	•						•		
	Meggering and thumb tests			•			•				
	Insulation resistance and hi-potential test							•			
	Partial discharge diagnostics										•
	No test (Run-to-Fail) mode			•	•		•				
Investigation Process (Several factors need to be observed and controlled if possible)	Temperature	•	•	•				•			
	Treeing	•	•								
	water damage	•	•		•	•	•	•		•	
	Degradation in insulation level	•			•	•	•	•	•	•	•
	Aging					•					
Cable Replacement Strategies	When cable failures have a major impact to the operations			•	•		•				•
	Smart replacement system			•							
	Part of substation renewal projects	•						•	•		
Techniques to Enhance Cable Lifespan	Cable jacketing		•						•		
	Specially designed taps		•								
	PVC sealed cages		•								

Summary Chart for Case Studies

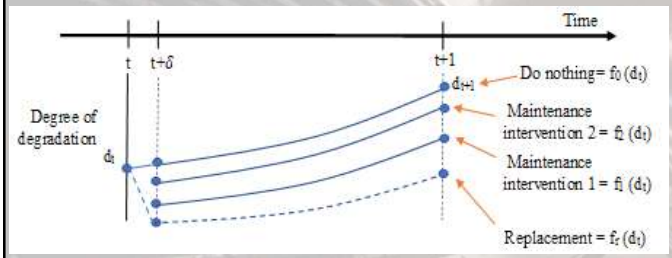
Part V.
Cable Replacement

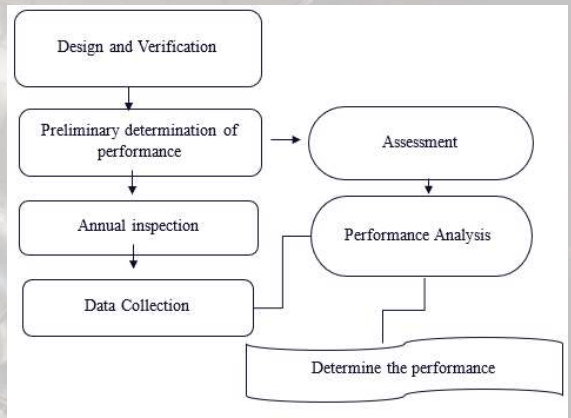
Cable Replacement



- 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.

Degradation Model for the Optimization Process





Performance Determination

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

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1. Data Collection for Descriptive Analytics

1.1. Cable Capital Example

Location	Insulation Type	Jacket Type	Con duit	Rated Voltage	Install ation Year	Length of the Cable Segment	Presence of Water	Corrosio n	Exposure to Extreme Temperatures	Undergro und/Over head	Maintenance frequency per year
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

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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

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1. Data Collection for Descriptive Analytics

1.2. Historical Failure Data Example

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

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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

- Cable ID
- Preventive Maintenance date
- Preventive Maintenance type
- Cost of Preventive Maintenance

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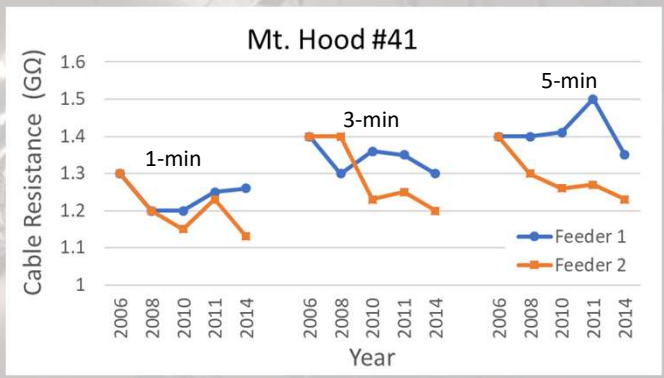
1. Data Collection for Descriptive Analytics

1.3. Testing and Preventive Maintenance Data Example

FEEDER CABLE MEGGER LOG			
Mt. Hood #41			
DATE		Feeder 1 (Ω)	Feeder 2 (Ω)
2/15/2006	1 Min	1.3G	1.3G
	3 Min	1.4G	1.4G
	5 Min	1.4G	1.4G
3/5/2008	1 Min	1.2G	1.2G
	3 Min	1.3G	1.4G
	5 Min	1.4G	1.3G
6/4/2010	1 Min	1.2G	1.15G
	3 Min	1.36G	1.23G
	5 Min	1.41G	1.26G
2/22/2011	1 Min	1.25G	1.23G
	3 Min	1.35G	1.25G
	5 Min	1.5G	1.27G
6/12/2014	1 Min	1.26G	1.13G
	3 Min	1.30G	1.20G
	5 Min	1.35G	1.23G



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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

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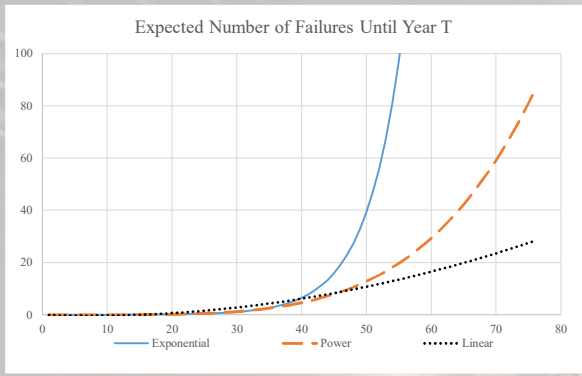
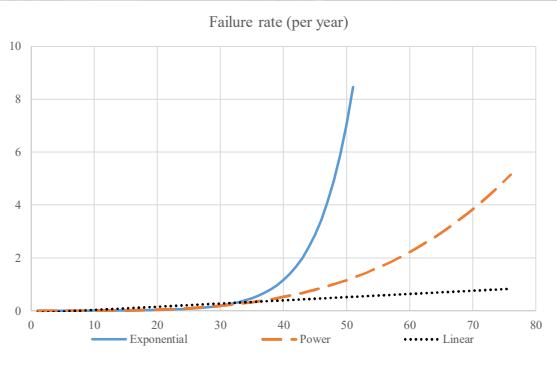
The estimation of failures



(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

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3. Prescriptive Analytics

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)

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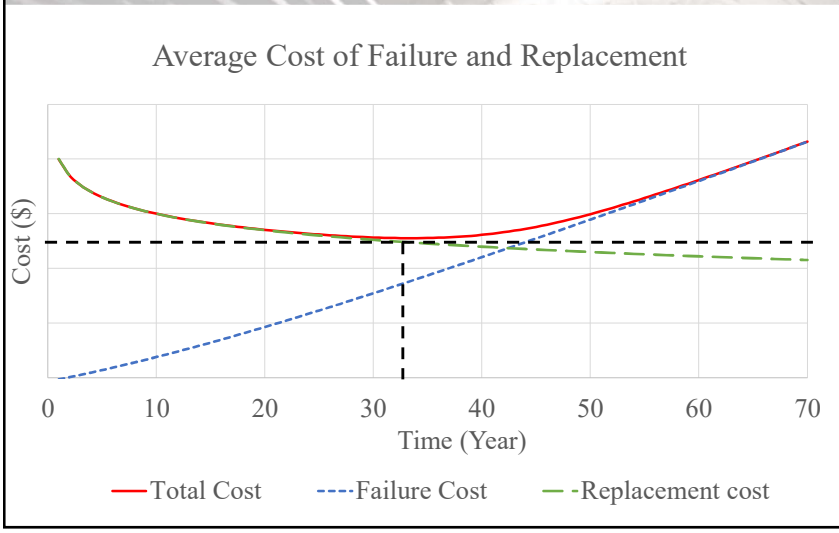
3. Prescriptive Analytics

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

3. Prescriptive Analytics

3.2. Cable Replacement

Optimal replacement time (in years)

	Ratio of Failure Cost to Replacement Cost				
	1-to-1	**1-to-10**	**1-to-50**	**1-to-100**	**1-to-200**
Exponential	23	33	41	44	48
Power	22	36	51	58	69
Linear	15	41	80+	80+	80+

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.

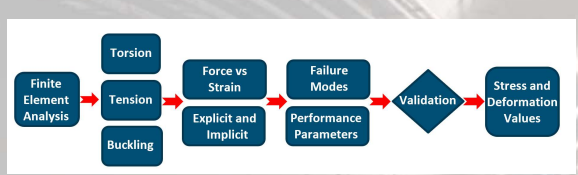
2- For each link on each network, if possible
   a. Cable repair cost should be estimated (material, labor, etc.).
   b. Cable failure cost should be estimated (repair cost and cost due to loss of passengers).
   c. Cost of cable replacement should be estimated (material, labor, loss of passengers, other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

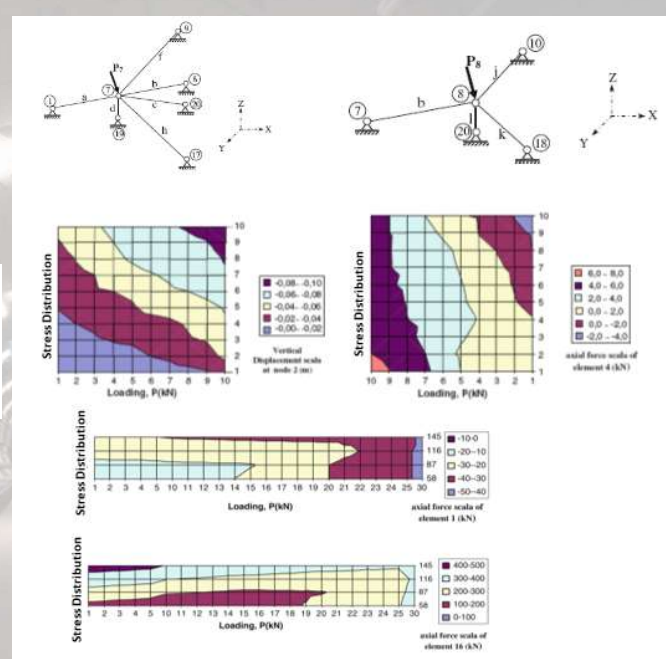
   Otherwise, the ratio between failure and replacement costs is estimated based on historical data or expert opinion.

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

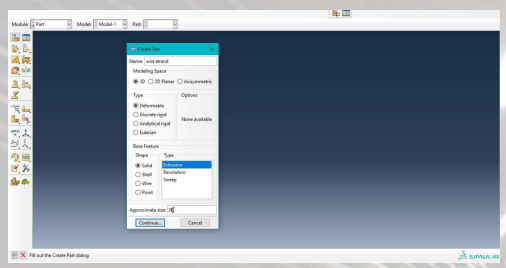
4- Identify groups of cables (two or more) that requires the closure of the same transportation lane and are in close proximity to each other. Identify the replacement cost of the group of cables and check if cases a or b in Equations (5.10) and (5.11) holds true. Accordingly, determine whether replacing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

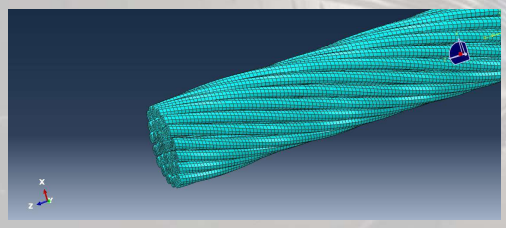
Finite Element Analysis

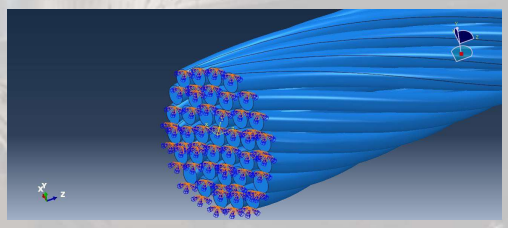




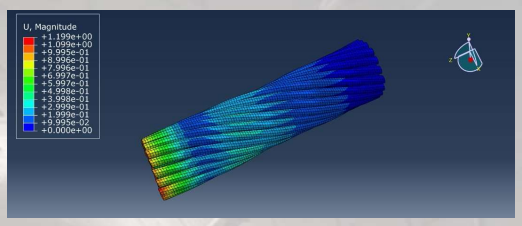
Finite Element Modelling

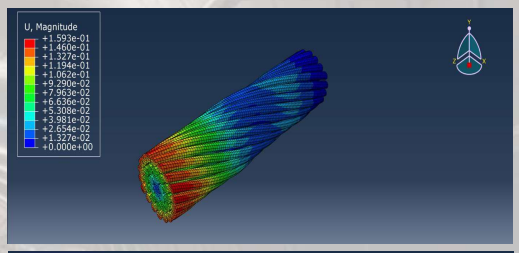


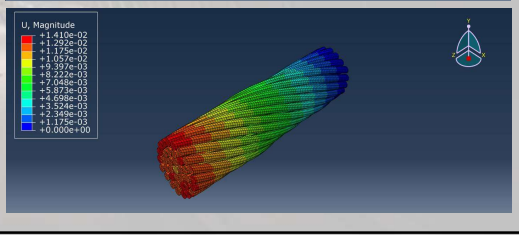




Stress Distribution under Tension, Torsion and Thermal Loadings







Part VI. Conclusions

Conclusions

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

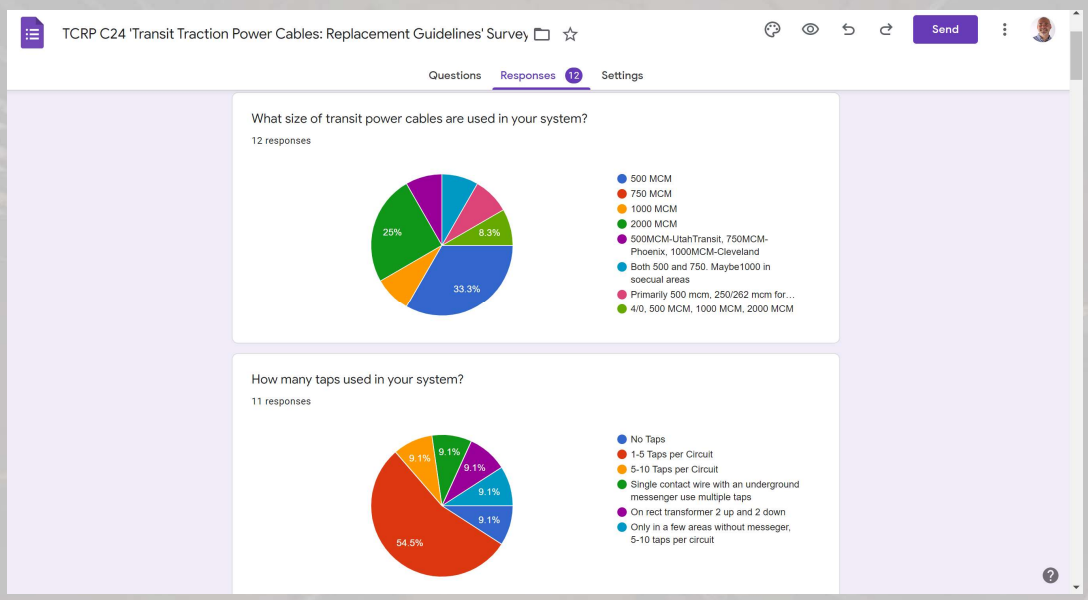
The significant results:

- 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 feed back and to keep in touch:

https://forms.gle/2N9CSs8MbX9tLpS87