Final Report

Damage to ITS, Traffic Control and Roadway Lighting Equipment From Transient Surge and Lightning Strikes

FDOT Contract No. BDV30-977-09
FSU Project ID # 034543 and 034982

Project Task Period of Performance:
4/30/2014 – 11/30/2016

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November 2016

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METRIC CONVERSION FACTORS

1 ft. = 0.3048 m
1 mph = 1.609 km/hr.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

Damage to ITS, Traffic Control and Roadway Lighting Equipment from Transient Surge and Lightning Strikes

5. Report Date

November 2016

6. Performing Organization Code

7. Author(s)

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8. Performing Organization Report No.

9. Performing Organization Name and Address

Department of Electrical and Computer Engineering
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10. Work Unit No. (TRAIS)

11. Contract or Grant No.

BDV30-977-09
April 2014 – November 2016

12. Sponsoring Agency Name and Address

Florida Department of Transportation (FDOT)
605 Suwannee Street, MS 30
Tallahassee, FL 32399

13. Type of Report and Period Covered

Final Report
April 2014 – November 2016

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The goal of this project was to collect the knowledge needed for the FDOT to either confirm or improve the adequacy of the FDOT's existing minimum standards for lightning/surge protection, including devices used and installation procedures. The project was conducted in four (4) tasks:

- Task 1: State of the Practice/Best Practice Study and Literature Search
- Task 2: Review of the IEEE Recommended Impulse
- Task 3: Review of the Effectiveness of Lightning Termination Devices
- Task 4: Final Report.

The research conducted for this project included surveys of FDOT districts and other state DOTs with similar lightning environments, literature searches to determine the proper techniques to test surge protective devices (SPDs) and best practice in designing lightning protection systems, design and construction of an SPD test laboratory, and analyses of NFPA 780 and other related standards with respect to the most appropriate standards to employ in designing lightning protection systems for FDOT roadside equipment.

The results from this project included equipment and test procedures for an SPD test laboratory, recommendations for improved maintenance reporting to improve identification of lightning-related damage, and lightning protection system design recommendations. Implementing these recommendations will reduce the FDOT maintenance costs and improve the reliability of intelligent transportation system (ITS), traffic control, and roadway lighting equipment.

17. Key Word	18. Distribution Statement
Lightning, Surge Suppression, Testing	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	95	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Acknowledgements

The author wishes to acknowledge the support and assistance of the Project Manager, Mr. Jeffrey Morgan of the FDOT Traffic Engineering and Operations Office's Traffic Engineering Research Lab (TERL).

The author also wishes to acknowledge the efforts of the graduate and undergraduate research assistants on this project:

Graduate Research Assistants: Muhammad Imran
Akbar Quraishi

Undergraduate Research Assistants: Dillon Wiggins
Alain Davila

Executive Summary

The Florida Department of Transportation (FDOT) has a large number of installations along the roads and highways in Florida. These installations include devices for traffic control and monitoring, Intelligent Transportation Systems (ITS), and roadway lighting. However, in Florida, there is a high risk of damage to exposed roadside equipment from direct lightning strikes and the residual current from nearby lightning strikes. Current lightning protection standards are intended to protect equipment in buildings or large structures and not always applicable to roadside equipment installations. Therefore, the goal of this project is to develop a credible and verifiable understanding of the lightning threat to roadside equipment, and develop a set of best practices to protect the roadside equipment from lightning damage without incurring unnecessary costs.

The intent of this project was to collect the knowledge needed for the FDOT to either confirm or improve the adequacy of the FDOT's existing minimum standards for lightning/surge protection including devices used and installation procedures. The project was conducted in four (4) tasks:

- Task 1: *State of the Practice/Best Practice Study and Literature Search*
- Task 2: *Review of the IEEE Recommended Impulse*
- Task 3: *Review of the Effectiveness of Lightning Termination Devices*
- Task 4: *Final Report.*

The research conducted for this project included surveys of FDOT districts and other state DOTs with similar lightning environments, literature searches to determine the proper techniques to test surge protective devices (SPDs) and best practice in designing lightning protection systems, design and construction of an SPD test laboratory, and analyses of NFPA 780 and other related standards with respect to the most appropriate standards to employ in designing lightning protection systems for FDOT roadside equipment.

The results from this project include equipment and test procedures for an SPD test laboratory, five (5) recommendations for improved maintenance reporting to improve identification of lightning-related damage, and lightning protection system design recommendations. The 5 recommendations are:

1. Provide statewide minimum lightning protection standards for all roadside installations.
2. Use the standard IEEE combination waveform (1.2/50 μs voltage / 8/20 μs current) to evaluate and approve the performance of SPDs used in ITS installation in Florida.
3. Test SPDs for both initial performance and resilience.
4. Improve and standardize the template for maintenance reporting for ITS and other FDOT roadside installations.
5. A set of recommendations for lightning protection system design based on existing standards that apply to roadside equipment.

Implementing these recommendations will reduce the FDOT maintenance costs and improve the reliability of intelligent transportation system (ITS), traffic control and roadway lighting equipment.

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1 Introduction

The Florida Department of Transportation (FDOT) has a large number of installations along the roads and highways in Florida that must be maintained. These installations include devices for traffic control and monitoring, Intelligent Transportation Systems (ITS), and roadway lighting. However, in Florida there is a high risk of exposed roadside equipment being damaged by direct lightning strikes and the residual current from nearby lightning strikes. Currently, the FDOT attempts to use approaches based on industry standards to protect the roadside equipment using lightning rods (air terminals) and surge protection devices (SPD) to divert the current from the lightning around the sensitive electronics to earth ground. The potential problem with the current lightning protection methods is that industry standards are nearly universally focused on devices in or near large structures or buildings. Relying on manufacturer and vendor recommendations for surge protection may not be reliable as the vendors may have some biases since they also sell the protection devices. Therefore, the goal of this project is to develop a credible and verifiable understanding of the lightning threat to roadside equipment and to develop a set of best practices to protect the roadside equipment from lightning damage without incurring unnecessary costs.

The Department of Electrical and Computer Engineering at the FAMU-FSU College of Engineering (COE) was contracted to provide support to the Traffic Engineering and Operations Office's Traffic Engineering Research Lab (TERL) of the FDOT with the goal of collecting the knowledge needed for the FDOT to verify or improve the FDOT's existing minimum standards for lightning/surge protection including devices used and installation procedures.

The project is being conducted in four tasks:

Task 1: State of the Practice/Best Practice Study and Literature Search
Task 2: Review of the IEEE Recommended Impulse
Task 3: Review of the Effectiveness of Lightning Termination Devices
Task 4: Final Report

This is the final report (Task 4) for this project. Sections 2–4 contain summaries, conclusions and recommendations resulting from the efforts undertaken in Tasks 1–3. More details of these efforts are contained in the individual task reports previous submitted to the FDOT.

Section 5 contains the overall conclusions and recommendations from the project.

Section 6 contains the benefits of the project for the FDOT.

2 Summary of Task 1: State of the Practice/Best Practice Study and Literature Search

Task 1 consisted of two (2) efforts:

Effort 1: Literature Search
Effort 2: Identify the Current State of the Practice and Best Practices in Florida

The following sections (Section 2.1, 2.2 & 2.3) are summaries of the three (3) deliverables delineated in the *Exhibit A – Scope of Service* for this project. The deliverables are as follows:

1. Literature Search Report (Section 2.1)
   A literature search report that identifies similar SPD studies completed along with a summary of results and recommendations.

2. State of the Practice and Best Practices in Florida (Section 2.2)
   A report that identifies the current State of the Practice and Best Practices in Florida. This report must detail the following:
   a. Current lightning and surge protection practices used by transportation practitioners.
   b. The number and location of sites with significant exposure to damaging surges.
   c. The quantity and location of equipment failures caused as a result of lightning and surge.
   d. The frequency and failures that are directly related to surge events.
   e. The number of SPD failures that have protected the attached equipment and what has worked best to generally prevent surges from damaging equipment.

3. Assessment of Uniformity of Lightning Surges and Protective Measures (Section 2.3)
   A report that identifies if lightning/surge events are similar regardless of the site location and if different protective measures are needed for different areas of the state when it comes to designs for grounding/bonding and selection of SPDs (due to differences such as predominant soil conditions, etc.).

2.1 Literature Search Report

> *A literature search report that identifies similar SPD studies completed along with a summary of results and recommendations.*

In order to assess the state of practice for surge protection applied within the scope of this research project, the research team at the FAMU-FSU College of Engineering conducted a literature search of technical publications, collected information on applicable standards, conducted a survey of other state DOTs, and collected information on commercially available surge Protective Devices.

2.1.1 Literature Search of Technical Publications

A general literature search was conducted to determine if similar studies of lightning surge suppression had been conducted in the past 15 years. The journal and conference publications of the Institute of Electrical and Electronics Engineers (IEEE) were searched along with more general searches of scientific and engineering publications. Most of the publications related to surge suppression were focused on the protection of electric power systems and improvements of standards for lightning protection. There has also been some research related to characterizing lightning strikes and testing the effects of lightning in various scenarios not directly related to the implementation of devices within the scope of this research project. The International Center for Lightning Research and Testing (ICLRT) at the University of Florida is one notable source of this type of research. Although studies noted during this literature search may not be directly related to the installation and protection of devices within the scope of this research project, related standards were surveyed for applicability.

2.1.2 Assessment of Applicable Surge Suppression Standards

A search was conducted to identify and assess standards that are related to, or can be applied to, the protection of devices within the scope of this research project. While there are a large number of standards related to surge protection, the following were identified as being most related to the protection of devices within the scope of this research project:

- UL 1449: Standard for Safety for Surge Protective Devices, 4th edition
- NEMA TS 2-2003 (R2008): Traffic Controller Assemblies with NTCIP Requirements,
- IEEE standards for low-voltage (1000 V and less) AC power circuits and for data, communication and signaling,
- NFPA 780: Standard for the Installation of Lightning Protection Systems, and
- ITU-T Series K: Protection Against Interference (recommendation)

2.1.3 Survey of Other State DOTs for Related SPD Studies

A survey was conducted of DOTs from states other than Florida to collect information on lightning protection measures used and what SPD studies had been conducted. The states surveyed included states where the largest number of lightning flashes were detected (from

Vaisala's U.S. National Lightning Detection Network). The states included in the survey were (responses were received from the states in **bold**):

- **Alabama**
- Arkansas
- Georgia
- **Louisiana**
- **Mississippi**
- North Carolina
- **Tennessee**
- **Texas**

Contacts within each state were identified using the state's DOT website or through known contacts. Each state was contacted via email of telephone and asked the following survey questions:

1. What standards or methods are used in your state to protect roadside ITS, traffic control and lighting from surges due to lightning?
    a. Can I get drawings of standard installations including lightning protection?
    b. Do you have a standard set of surge protectors that you use or have approved for use?
2. Has your state conducted any studies on surge protection devices (SPDs) or surge protection techniques?
    a. Any laboratory of field test studies conducted?

A summary of the responses received from the state survey are provided in Table 2.1. The states that responded indicated that they had not conducted any recent testing related to surge protection for devices within the scope of this research project. Each of the states had different levels of surge protection standards. Most of the states had some typical SPD drawings or standards for the SPDs for at least some installations.

The SPD standards for LED roadway lighting in Texas differed from those in the other states in that the SPDs were required to be tested using multiple surge waveforms. The specification in Texas required the SPDs to be tested using the following waveforms:

1. "C Low Ring Wave" as defined in IEEE C62.41.2-2002, Scenario 1, Location Category C;
2. "C High Combination Wave" as defined in IEEE C62.41.2-2002, Scenario 1, Location Category C; and
3. "Electrical Fast Transient Bursts," as defined in IEEE C62.41.2 -2002.

State	Question 1) Lightning Protection Standards	Question 2) Lightning Protection Studies
Alabama	• Sent excerpts from 2014 ALDOT Standard and Special Drawings for Highway Construction. o Called for a minimum of one 12 inch ground rod driven into the ground. Additional rods added to get a maximum of 25 Ohm ground resistance. • Indicated that ITS does not have Standard Drawings.	• Have not conducted any field tests. • Field electrician attends NEC training courses annually and advises on changes to the standard drawings required for code compliance.
Louisiana	• Sent drawing of SPD installations for cabinets and CCTV cameras with lowering mechanism. • Sent specifications for surge protective devices for power video and data (serial/Ethernet) lines. o 1 – 13 kA discharge current depending on type. o DIN rail mounting. o Atlantic Scientific Zone Barrier (or equiv.).	None indicated.
Mississippi	• Sent typical drawings for lightning protection on high mast pole & power controller wiring. • No standard drawings; designers start with current drawing and design to meet standards (NEMA, UL,...). • Indicated that there was not much of a problem with lightning damage to roadway lightning.	• Indicated that a project was conducted on the effectiveness of static dissipaters in which the dissipaters were not found to be effective.
Tennessee	• Currently working on completing standards and Qualified Products List for the ITS network. • Sent some excerpts from the Technical Special Provisions being used for some projects regarding surge protection. o UL and IEEE/ANSI standards met. o 3 – 10 kA peak surge (8/20 us waveform) CCTV o 70 kA peak surge on ac power.	None indicated.
Texas	• Sent example drawings of roadway lighting with lightning rods, down conductors and 10-ft ground rods. • New LED lights require SPDs. Sent specifications including SPDs for LED Roadway Luminaires. o 10 kA peak surge, multiple waveforms. • Signals Specifications: MOV for all wires entering cabinet, SPDs and filters on power panels, SPDs on coaxial cables.	• Research conducted approximately 30 years ago for NEMA TS2 standards.

Table 2.1. Summary of Responses from Survey of States

In addition to the survey that was sent to the state DOTs, the research team reviewed the websites of 17 state DOTs (other than Florida) with the highest average lightning flash density (based on data from Vaisala available on the NOAA/National Weather Service Lightning Safety website[1]). A summary of results from the survey of these state DOT websites, listed in order of highest flash density, is provided in Appendix A. These results along with the survey of states demonstrate that the completeness of ITS-related lightning protection standards and the types of protection used varies widely across these states. Texas, ranked 18th in lightning flash density, had the most detail available on surge protection used. However, Mississippi, ranked 3rd in lightning flash density, has no standard drawing for lightning protection but instead allows designers to start with current drawing and design to meet standards (NEMA, UL,...).

2.1.4 Commercially Available Surge Protective Devices

A search was conducted to collect a list of the commercially available surge protection devices (SPDs) that may be suitable for use with devices within the scope of this research project. First, the SPD manufacturers and products on the FDOT Approved Product List (APL) were identified. These are listed in Table 2-2. Next, a search was conducted to identify commercially available SPDs that also may potentially be suitable for use in FDOT systems. The search revealed 19 companies that produce SPDs and 132 SPD (or SPD series) that are currently commercially available. A spreadsheet of the SPDs along with their pertinent operating parameters was prepared. This list of SPDs will be used in future tasks under this project.

2.1.5 Conclusions from the Literature Search

The literature search and review of technical publications did not reveal any SPD studies similar to the efforts being conducted under this project. Most of the literature discussed surge protection for power systems including power distribution and generation. However, the literature search, standards assessment, surveys and SPD data collection has provided considerable information that will be very useful in the remaining tasks under this project. There is considerable information concerning SPDs including standards, recommendations and current practice that can be evaluated when determining specifications for lightning surge protection for devices within the scope of this research project.

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[1] "Number of Cloud-To-Ground Flashes by State from 1997 to 2011." Internet: NOAA/National Weather Service Lightning Safety, June 5, 2012 [December 10, 2014].

Company Name	Device Name	Model	Operating Voltage	Operating Current	Max Let-Through Voltage	Max Rated Surge Current	Approval Date
Advanced Protection Technologies Inc.	Surge Protector	SPDee S-kit	120 -600 V		690 V	200 kA	11/16/2010
Advanced Protection Technologies Inc.	Surge Protector	TE(xx)XCS104XA Series	120-277 V			200 kA	2/11/2011
Advanced Protection Technologies Inc.	Surge Protector	TE(xx)XDS(yy)4XA Series	120-277 V			200 kA	6/15/2011
Citel, Inc	Surge Protector	DLA Series	6-48 V		53 V	20 kA	8/6/2013
Citel, Inc	Surge Protector	DS2x0-xxDC	24-48 V		65 V	30 kA	8/6/2013
Citel, Inc	Surge Protector	MJ8 Series	8-60 V	600-650 mA		2 kA	8/6/2013
Citel, Inc	Surge Protector	DINBNC-HD	2.7 V	750 mA		132 A	8/6/2013
Cooper Crouse-Hinds MTL	Surge Protector	41003TC					5/25/2005
Cooper Crouse-Hinds MTL	Surge Protector	ZoneDefender Pro	120 V			120 kA	12/18/2009
Emerson Network Power	Surge Protector	PC642	5-180 V	150 mA	200 V	10 kA/phase	7/1/1985
Emerson Network Power	Surge Protector	SRA16C-1	75 V			10 kA/phase	8/16/1983
Emerson Network Power	Surge Protector	SRA6LCA	75 V		130 V	250 A	7/28/1986
Emerson Network Power	Surge Arrestor	SPA-100T	120 V		395 V	13 kA/phase	12/10/1982
Emerson Network Power	Surge Protector	SHP300-10	120 V	10 A	395 V	58.5 kA	2/10/1984
Emerson Network Power	Surge Protector	SHA-1210	120 V	10 A	395 V	39 kA/phase	5/16/1991
Emerson Network Power	Surge Protector	ACP-340	120 V	10 A	395 V	39 kA/phase	5/16/1991
Emerson Network Power	Surge Protector	SHA-1230FS-T	120 V	30 A	400 V	100 kA/phase	8/9/2012
Emerson Network Power	Surge Protector	SHA-4803	480 V	100 mA	1500 V	39 kA/phase	5/14/1982
Emerson Network Power	Surge Protector	SRA 6 LC	75 V		130 v	250 A	5/14/1982
Emerson Network Power	Surge Arrestor	SRA64C-008D			200 V	10 kA/phase	12/10/1982
Emerson Network Power	Surge Protector	CX06 Series	5 V	150 mA	6 V	20 kA	1/22/2014
Emerson Network Power	Surge Protector	PowerSure 400 Series	120 V		150 V	200 kA	4/1/2013
Hesco RLS Inc	Surge Protector	HE300-15	120 V	15 A	478 V	46 kA/phase	7/26/1985
Hesco RLS Inc	Surge Protector	HE642C	212 V	1 A	30 V	10 kA	7/29/1999
Hesco RLS Inc	Surge Protector	HE1700		15 A	395 V	66 kA	7/29/1999
Hesco RLS Inc	Surge Protector	HE1800		15 A	395 V	66 kA	2/2/2001
Hesco RLS Inc	Surge Protector	VLP Series			25 V	1 kA	2/2/2001
Meter-Treater	Surge Protector	CLT-CCV-2-M-5			11 V	10 kA	11/15/2012
Meter-Treater	Surge Protector	SLT/IM-04S-U Series			41.4 V	10 kA	11/15/2012
Meter-Treater	Surge Protector	RCHW Series	120 V		150 V	200 kA	4/3/2013
Peek Traffic Corp	Surge Protector	G.E. Type V150HE150					11/2/1982
Trafficware Group Inc	Surge Protector	SRA-6LC			25 V	750 kA	7/16/2001

Table 2.2. Surge protection Devices (SPDs) Listed on the FDOT Approved Product List (APL)

2.2 State of the Practice and Best Practices in Florida

A report that identifies the current State of the Practice and Best Practices in Florida. This report must detail the following:

1. *Current lightning and surge protection practices used by transportation practitioners.*
2. *The number and location of sites with significant exposure to damaging surges.*
3. *The quantity and location of equipment failures caused as a result of lightning and surge.*
4. *The frequency and failures that are directly related to surge events.*
5. *The number of SPD failures that have protected the attached equipment and what has worked best to generally prevent surges from damaging equipment.*

The primary method used to collect the data to complete this effort was a survey sent to each of the FDOT districts. To develop the survey, the topic of lightning protection was discussed with personnel from the FDOT Traffic Engineering Research Lab (TERL), FDOT District 7, Hillsborough County DOT, and Emerson Network Power - Advanced Protection Technologies (APT). The discussions included grounding techniques, lightning rods (air terminals), direct lightning strikes, maintenance records and surge protection devices (SPDs). From these conversations a survey questionnaire was developed in an attempt to collect the information from each of the 8 FDOT district office (District 1 – 7, and the Turnpike District). The survey consisted of the following five (5) questions:

1. Please provide monthly repair information (cost and/or # repairs) of ITS equipment for the past 5 years (if possible). ITS equipment can include traffic monitoring equipment, traffic cameras, DMS and lighting. While it is not generally possible to identify most lightning damage, the goal is to identify the increase in maintenance required during the peak lightning months.
2. Please provide installation drawings including the lightning protection methods (including grounding, air terminals, type of surge suppression devices (SPDs) used, and location of SPDs) employed at typical ITS installations.
3. Please provide installation drawings including the lightning protection methods employed at a "best practices" ITS installation.
4. Please identify any significant changes in the last 5 years to lightning protection systems in your district. Changes can include grounding, air terminals, type of surge suppression devices (SPDs) used, and location of SPDs in your ITS installations.
5. Please estimate the average number of direct lightning strikes causing damage to ITS equipment in your district. Please provide examples of damage caused by direct lightning strikes to ITS equipment. For each example please try to provide information on the lightning protection equipment at the site, a list of the damages caused by the lightning and pictures of the lightning damage.

The survey was initially sent to the District Traffic Operations Engineer (DTOE) for each of the 8 districts. Typically the DTOE would refer the survey to district personnel or maintenance subcontractors who could provide the information requested. Most of the state districts provided information in response to one or more of the questions in the survey. In the following sections the information provided will be assessed to identify the State of the Practice and Best practices in Florida.

2.2.1 Conclusions from the Study of the State of the Practice and Best Practices in Florida

The assessment of the State of Practice and the Best Practices in Florida was conducted through conversations with FDOT personnel from the Florida DOT district offices and the results of the survey sent to each district. These efforts were designed to try to answer the 5 questions stated at the beginning of Section 3. Below are the conclusions and comments related to each of these questions.

Question 1. Current lightning and surge protection practices used by transportation practitioners.

A majority of the districts in Florida use the standards and specification set forth by the state offices of FDOT. The lightning and surge suppression practices typically have the following characteristics:

- Use SPDs of the FDOT Approved Product List (APL).
- Have a single point ground system with a ground rod array having the goal of a ground resistance <= 5 ohms (FDOT specified).
- Use one or more air terminals (lightning rods) on raised structures depending on the size and configuration of the structure. Placement generally follows NFPA guidelines.

Some districts have found that replacing SPDs with newer models have improved protection. District 7 has experimented (apparently successfully based on anecdotal evidence) with surge protection strategies that exceed those in the State requirements. For example, District 7 found that placing SPDs on the service and cabinet sides of the power transformers provides greater protection for the transformers. In addition, the experiments have reinforced the importance of adhering to current FDOT standards (Florida Department of Transportation Standard Specifications for Road and Bridge Construction, 2014) and practices such as:

- Placing SPDs on both ends of any conductor that is routed underground or out of the cabinet to an elevated structure.
- Grounding SPDs using the shortest practical grounding wires. Also, not using the cabinet or the DIN rails for grounding.

Question 2. The number and location of sites with significant exposure to damaging surges.

The total number of ITS, traffic control and roadway lightning sites, and their locations was not provided by the districts. District 7 provided a Google Earth map of installations of ITS equipment. In this map many of the installation were only listed by highway/arterial and the mile markers. The number of ITS sites in the file was very high. For example, on I-4 the CCTV cameras were separated by up to 1 mile, however the MVDS poles were so numerous that they were not included in the map.

Question 3. The quantity and location of equipment failures caused as a result of lightning and surge.

Several districts provided summary work orders (or tickets) of maintenance actions on ITS equipment. Most of the information was provided was supplied by maintenance contractors. The format and detail of the summaries varied significantly making direct comparisons of lightning damage statistics difficult. The monthly summaries did however provide some indication of the relative impact of lightning damage on the maintenance requirement of the ITS systems. The average number of repairs (work orders) required during the summer peak lightning months (June-August) was compared to the average number of repairs required during the lower lightning months (October-April). The results (based on Districts 1, 6 & 7) showed that the overall number of work orders increased by 26% to 54% during the summer months. When just the work orders that can be classified as possible or likely lightning damage (Districts 6 & 7) the work orders increased 45.5% to 62% in the summer months.

Question 4. The frequency and failures that are directly related to surge events.

Very few work orders indicated directly that the damage was due to lightning. During the analysis of the work order summaries from Districts 6 & 7 the descriptions were detailed enough to identify damage that was potentially due to lightning (not explicit damage due to other identifiable sources) and damage that was likely due to lightning (including failures of SPDs, fuses, and other surge protection devices). In District 6, 87.4% of work orders were potentially related to lightning damage and only 1.3% of the damage could be listed as likely lightning damage. In District 7, the percentages were 93.7% potential lightning work orders and 0.6% likely lightning damage. Note that none of the work order descriptions included information on the weather when the damage occurred. Direct lightning strikes were seen as rare by the districts, although District 4 listed four direct lightning strike examples from January to June 2014.

Direct lightning strikes are likely a rare occurrence. Generally, whether or not the damage is directly attributable to lightning is not obvious in most cases. The number of repairs to equipment significantly increases during the summer months but the direct or suspected cause of equipment failure is difficult to determine and not necessarily reflected in the comments in the work orders.

Question 5. The number of SPD failures that have protected the attached equipment and what has worked best to generally prevent surges from damaging equipment.

The answer to this question can at present only be answered using anecdotal evidence. District 4 indicated that replacing obsolete surge protective devices (SPDs) on the power main disconnects has reduced equipment damage. In District 7 there is anecdotal evidence that placing SPDs on both the service and low-voltage sides of the 480V/120V power transformers has significantly reduced transformer damage. Also, District 7 has indicated that improving grounding paths from the SPDs has improved the protection to the ITS equipment. More data and study is needed to answer this question with confidence.

2.3 Assessment of Uniformity of Lightning Surges and Protective Measures

> *A report that identifies if lightning/surge events are similar regardless of the site location and if different protective measures are needed for different areas of the state or if "one size fits all" when it comes to designs for grounding/bonding and selection of SPDs (due to differences such as predominant soil conditions, etc).*

One of the goals of the efforts under this task of the project was to determine if the lightning protection measures for ITS, traffic control, and roadway lighting systems should be uniform across all of Florida, or if more costly protection measures need to be used only in areas of higher lightning density. This section summarizes the efforts undertaken to assess the lightning surge protection measures across the state and to quantify the damage caused by lightning in the FDOT districts.

2.3.1 Results from District Work Orders

The survey of the eight FDOT districts (Section 2.2) provided the majority of the information used to assess the geographic variance in lightning surge events across Florida. Four districts provided maintenance data that can be used to gauge the relative effects of lightning on the maintenance activities required. There were very few records in the maintenance data provided that specifically identified lightning surges as the cause for the damage. Therefore, to ascertain the effects of lightning on maintenance, the levels (number and/or cost) were compared for the peak lightning summer months (June-August) and the months of lower lightning levels (October-April).

The districts that provided monthly maintenance information were Districts 1, 2, 6, and 7. From the map of FDOT districts and the average lightning flash density map for Florida (from Vaisala[2]) in Figure 2.1 it can be seen that these districts represent a fair sampling of the lightning densities across the state. District 7 is on the west coast of Florida and has a very high lightning flash density ranging from eight to greater than 14 flashes per square kilometer per year (fl/sq km/yr). District 1 is a partly coastal and partly inland portion of the lower Florida peninsula and has areas with a range of flash densities from 6 to 14 fl/sq km/yr. District 2 is the northern section of Florida with coastal and inland areas and has a range of flash densities from 6 to 10 fl/sq km/yr. Finally, District 6 is a primarily coastal region at the tip of the Florida peninsula and has a range of flash densities from 4 to 10 fl/sq km/yr.

A summary of the increases in monthly work orders for each of the districts is provided in Table 2.3. The results show that the increase in the total number of work orders for ITS maintenance increases from 26–75% (26–54% excluding District 2, which provided only one year of data) during the peak summer lightning months. In Districts 6 and 7, the amount of increase during the summer lightning months was 5–8% more when considering only work orders that are possibly or likely related to lightning damage.

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[2] "Vaisala's National Lightning Detection Network (NLDN) Cloud-to-Ground Lightning Incidence in the Continental U.S. (1997-2010)." Internet: http://www.vaisala.com/, 2011 [July 23, 2014].

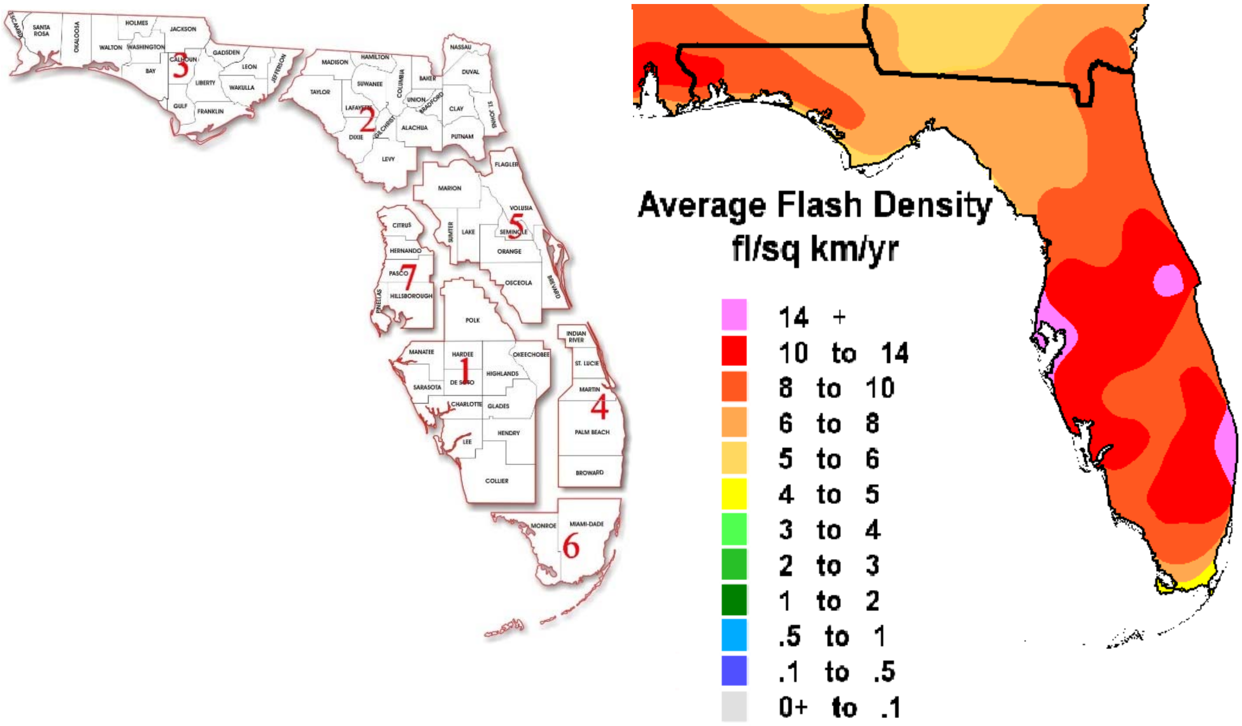


Figure 2.1. Map of the FDOT Districts 1 – 7 and the Lightning Flash Density in Florida (Vaisala[2])

District #	Flash Density Range (fl/sq km/yr)	Percent Increase in Work Orders in Peak Lightning Months	# Years of Data
1	6 to 14	26% (total work orders)	4.5
2	6 to 10	75% (devices replaced)	1
6	4 to 10	54% (total work orders) 62% (possible + likely lightning related work orders)	2.5
7	8 to >14	40% (total work orders) 45% (possible + likely lightning related work orders)	4

Table 2.3. Summary of Work Order Increases during Summer Peak Lightning Months

In addition to the maintenance information, the districts also provided information on the typical and "best practice" ITS installations with respect to lightning surge protection. All districts reported that the typical installation were all designed to meet the Florida state-wide standards and specification, and the SPDs used were typically those on the Approved Product List (APL). Only District 7 reported some significant "best practice" modifications added to some installation to improve the overall surge protection.

2.3.2 Analysis and Conclusions

District 7, which has the highest average lightning flash density in the state, reported one of the lower increases in total work orders during the summer at 40%. By contrast, District 6, which had the lowest range of flash density, reported a higher increase in work orders during the summer months at 54%. The data from all districts providing ITS maintenance information in response to the survey demonstrates a significant increase in work orders or replaced devices during the peak summer lightning months. Therefore, improving the lightning surge protection measures can provide a significant savings in maintenance costs state wide.

The anecdotal evidence of improved surge protection using best practices and the lower increase in monthly maintenance during the summer months in District 7 provide evidence that there can be significant improvements in surge protection measures over the current state standards. Further efforts are needed to identify the most effective surge protection techniques. Improved maintenance reporting templates are needed (see Section 3.4) to more accurately monitor lightning damage and assess the effectiveness of improvements to surge protection measures.

2.4 Conclusions from Task 1

The literature search effort under Task 1 resulted in the collection of considerable information concerning SPDs including standards, recommendations and current practice that can be evaluated when determining specifications for lightning surge protection of ITS, traffic control and roadway lighting systems. There were no reports found during a search of technical literature nor any information in the survey of other state DOTs concerning similar studies of lightning surge protection for ITS, traffic control or highway lighting equipment. However, the effort collected a significant number of related standards and information on commercially available SPDs.

The assessment of the state of practice and "best practices" in Florida was conducted primarily through a survey sent to each of the FDOT districts. This survey revealed that almost all ITS installations are constructed using the surge protection standards and specifications provided at the state level in the FDOT Standard Specifications for Road and Bridge Construction. District 7 has experimented with a few enhancements of the surge suppression measures specified including adding additional SPDs and improving the ground wiring of the SPDs. The sheer number of ITS, traffic control and roadway lighting installations made it prohibitive to evaluate sites individually, but several districts provided maintenance records showing a 26 – 54% increase in repairs during the summer peak lightning months.

The lightning flash density average across the state (from Vaisala[2]) showed that the flash density was high in all parts of the state of Florida ranging from 4 to over 14 lightning flashes per square kilometer per year. The ITS work order statistics showed that all reporting districts had a significant increase in work orders during the summer peak lightning months and that the variations in flash density across the state had little correlation with the increase in summer work orders. Considering that most of the districts use the same standards for ITS surge protection, it is possible that improving and standardizing surge protection measures further can provide additional savings in maintenance costs statewide. But, it appears from this research that no FDOT district in the state needs "better" specifications or standards.

3 Summary of Task 2: Review of the IEEE Recommended Impulse

Task 2 consisted of five (5) efforts:

- Effort 1: Review of the IEEE Recommended Impulse (8x20µs 6kV/3kA Combination Wave).
- Effort 2: Review of Industry Standard Lab Environment/Equipment and Testing Procedures.
- Effort 3: Identify Test Equipment and Test Standards and Set up an SPD Test Lab.
- Effort 4: Perform a Review of Site Monitoring Tools and Reporting Procedures.
- Effort 5: Review Best Practices Used Outside of the State of Florida and Other Industry Standards Used to Protect Similar Equipment.

The following sections (Section 3.1 -3.5) correspond to the five (5) deliverables delineated in the *Exhibit A – Scope of Service* for this project. The deliverables are as follows:

1. Review of the 8x20µs 6kV/3kA Combination Wave (Section 3.1)
   A report that identifies why the 8x20µs 6kV/3kA combination wave was selected for the testing of SPDs and confirm the Department's minimum requirements do adequately protect the equipment , or make recommendations regarding let-through voltages, response times, current capacity, etc. which would adequately protect ITS, traffic control and roadway lighting equipment typically used by the Department.

2. Recommended Lab Environment/Equipment and Testing Procedures (Section 3.2)
   A report that identifies lab environment/equipment and testing procedures recommended for the testing of the SPDs in the FDOT's Approved Product List (APL) and subjected to the criteria recommended in deliverable 1 above (Section 3.1). The report must recommend commercially available tools and test equipment that can be used to perform industry-standard SPD performance evaluations (identifying purpose, make, model, specific configuration options, and cost).

3. SPD Test Lab and SPD Test Results (Section 3.3)
   A report that summarizes tests conducted and results using purchased equipment and recommended test procedures for each type of SPD specified in the Department's minimum specifications. All equipment purchased will be provided to the Department at the end of the project.

4. Site Monitoring Tools and Reporting Procedures (Section 3.4)
   A report that identifies site monitoring tools and reporting procedures that would aid in the collection of data to help keep track of equipment failures and associated repair and/or replacement costs.

5. Best Practices Nationally for Use of SPDs to Protect Similar Equipment
   (Section 3.5)
   A report that identifies best practices nationally regarding the use of SPDs to protect similar equipment and the applicability of other industry standards that could provide better protection of equipment without incurring unnecessary costs.

3.1 Review of the 8x20µs 6kV/3kA Combination Wave

> *A report that identifies why the 8x20µs 6kV/3kA combination wave was selected for the testing of SPDs and confirm the Department's minimum requirements do adequately protect the equipment, or make recommendations regarding let-through voltages, response times, current capacity, etc. which would adequately protect ITS, traffic control and roadway lighting equipment typically used by the Department.*

The selection of a waveform for testing SPDs has been a topic of discussion for decades. There have been many studies performed in an effort to characterize the lightning surge voltage and current waveforms. The results of the studies demonstrate that the waveform of a lightning surge varies greatly depending on multiple factors including the location or distance of the lightning strike, the type of coupling into the system being protected, the grounding and soil characteristics, and multiple other factors both within and beyond the control of the protection system designers. Therefore, it is not practical or even feasible to test SPDs using every potential waveform due to lightning surges. The approach of the applicable standards is to identify test waveform(s) that, when used appropriately to test SPDs, identifies which SPDs will perform well in the field.

To test the performance of surge protective devices (SPDs) for low-voltage (1000 volts RMS or less) AC power systems, the IEEE has developed standards, recommended practices and guides. The IEEE standards describe the surge environment, representation and amplitude of test waveforms, safety guidelines for testing, and applications of SPDs to low voltage power systems. These standards were designed specifically for lightning protection within structures or buildings. However, the use of these standards has been accepted for the testing of SPDs and thus is useful for understanding how to test the SPDs used in ITS applications.

IEEE STANDARDS

1. IEEE Standard C62.62^{TM}-2010 – "IEEE Standard Test Specifications for Surge-Protective Devices (SPDs) for Use on the Load Side of the Service Equipment in Low-Voltage (1000 V and Less) AC Power Circuits"
   The surge tests included in C62.62 are based on the electrical surge environment defined in IEEE Std C62.41.1-2002.
2. IEEE Standard C62.41.1-2002 – "IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits"
   The first in trilogy of standards.
3. IEEE Standard C62.41.2-2002 – "IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits"
   The 2nd in the trilogy of standards.
4. IEEE Standard C62.45-2002 – "IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V and Less) AC Power Circuits"
   The 3rd in the trilogy of standards.
5. IEEE Standard C62.72-2007 – "IEEE Guide for the Application of Surge-Protective Devices for Low-Voltage (1000 V or Less) AC Power Circuits"

3.1.1 The Surge Environment

The IEEE has made extensive effort to characterize the electrical surge environments for low-voltage systems. There are several documents that the IEEE uses to define surge environment:

- IEEE Standard C62.41.1-2002 – "IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits"
- IEEE Standard C62.42-2005 – "IEEE Guide for the Application of Component Surge Protective Devices for Use in Low-Voltage (1000 V (AC) or 1200 V (DC) or Less) Circuits"
- IEEE Standard 1100-2005 – "IEEE Recommended Practice for Powering and Grounding Electronic Equipment"
- IEEE Standard C62.48-2005 – "IEEE Guide on Interactions Between Power System Disturbances and Surge-Protective Devices"

There are two sources of electrical surges; 1) switching (power systems) and 2) lightning. The frequency of surges caused by lightning are much lower as compared to electrical surges caused by switching.

3.1.1.1 *Lightning*

Lightning is the natural phenomenon that causes electrical surges most frequently. Lightning that can damage electrical equipment can be divided into three types; direct strike to the electrical or power system, near strikes to the area surrounding the electrical system, and distant or far strikes.

Direct Lightning Strikes

During the direct strike of lightning to a structure or electrical system, the full effects of the lightning flash or stroke is directly coupled to the structure or electrical system. The electrical surge related to this type of event are most severe (highest magnitude), and can cause damage to both the electrical systems and the structure if not properly protected.

Nearby Lightning Strike

During a nearby lightning strike, the lightning interacts with electrical systems through magnetic coupling, capacitive or inductive coupling, and through galvanic currents through the ground. In this type of lightning surge, the threat to the electrical system is similar to that of the direct strikes except that the direct coupling effect is reduced by the fact that only a fraction of total lightning current is involved. SPDs installed on the electrical system are expected to be subjected to medium or moderate stress during this type of event.

Far Lightning Strike

During a far strike event the threat of induced currents (primarily galvanic currents through the ground) is even further reduced as compared to the direct or nearby strike due to the increased distance from the lightning channel to the impacted circuits. SPDs installed on the electrical system are expected to be subjected to a low stress during this type of event.

3.1.1.2 *Switching Surges*

Switching surges are more frequent in their occurrence but are not as damaging or disruptive to electrical circuits as lightning surges. Broadly switching surges can be classified into two types, 1) Intentional and 2) Unintentional.

Intentional Switching Surges

Often switching surges are caused by the normal and intended action of the electrical system and its components. These sources of surges are deliberately and frequently activated and their actions are completed repeatedly and regularly, as part of the normal operational function of the electrical system. Following are the examples of sources of normal switching surges which are not considered as damaging or threat to the electrical systems.

- *Contractor, Relay and Breaker Operations*
- *Switching of Capacitor Banks*
- *Discharge of Inductive Devices*
- *Starting and Stopping of Loads*

Unintentional Switching Surges

In contrast to intentional switching surges, other sources of switching surges are caused by abnormal operation or fault and are mostly unintentional.

- *Arcing Faults and Arcing Ground Faults*
- *Fault Clearing*
- *Loose Connections*

3.1.1.3 *Surge Scenarios*

To aid in the classification or the surge environment, two scenarios, referred to as “Scenario I” and “Scenario II”, have been defined in the IEEE standards (in particular, C62.41.2-2002). The scenarios identify different levels and characteristics of stresses on the SPDs and the protected equipment. Note that these scenarios are defined in terms of the lightning flash, but switching surges are also included in the Scenario I.

Scenario I - Lightning Flash Not Directly Involving the Structure

Scenario I is the most common scenario for lighting surges. In this scenario the lightning flash is not directly striking the structure nor is it striking the ground in the immediate vicinity of the structure. There are 2 potential mechanisms creating the lightning surge events to interact with the structure (or in our particular case, the ITS installation).

The first mechanism is direct or indirect coupling of the lightning flash to the power lines or other electrical wires entering the structure. This could include direct flashes to adjacent structure with connections to the structure under consideration.

The second mechanism is electrical and magnetic fields from the lightning flash coupling inductively to the wires within the structure.

The primary protection for Scenario I surges are the SPDs installed at appropriate points where surges can occur. The SPD test environment is primarily designed to evaluate the performance of the SPDs in the more common Scenario I lightning environment and switching surges.

Scenario II – Direct Lightning Flash to or Very Near to the Structure

This scenario is much less common but can result in the most severe damage to the structure, SPDs or other electronics. The mechanisms for surges in this scenario include direct and indirect coupling to the power lines or other electrical wires entering or within the structure. In addition, the associated ground potential changes due to the lightning flash can also create surges into the structure as well.

The primary protection for Scenario II surges is the air terminals, conductor paths to carry the current to the ground, shielding inherent in the structure (e.g., metal cabinets or poles), and proper grounding to dissipate the energy. SPDs are needed to protect the equipment from the residual surges not completely dissipated to the ground and induced surges.

3.1.2 Location Categories

Based on the sources of surges and their strength, the location for SPDs installation is divided into three categories by following standards:

1. IEEE Standard C62.41.1-2002 – “IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits”
2. IEEE Standard C62.41.2-2002 – “IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits”

The three categories of SPDs are designated A, B and C. These categories are described in the following sections and depicted in Figure 3.1. These location categories are based on their proximity to the devices the SPDs are protecting and the structure housing the equipment. They were defined originally for power protection but have application for any SPD protecting electrical systems.

3.1.2.1 *Category C Location*

Category C location are as follows:

- Outside and including the service entrance equipment.
- Service drop from pole or transformer to a building.
- Conductors between the utility’s revenue meter and service entrance equipment.
- Overhead line to detached buildings.
- Underground line to a wall pump or other outdoor electrical equipment.

3.1.2.2 *Category B Location*

Category B location are as follows:

- Service entrance equipment located inside a facility, feeder circuits, and short branch circuits.
- Distribution panel boards and devices.
- Busways and feeders in industrial plants.
- Heavy appliance outlets with short connections to the service entrance equipment.
- Lightning systems in large building or facilities.

3.1.2.3 *Category A Location*

Category A location are as follows:

- All outlets at more than about 10 m from Category B.
- All outlets at more than about 20 m from Category C.

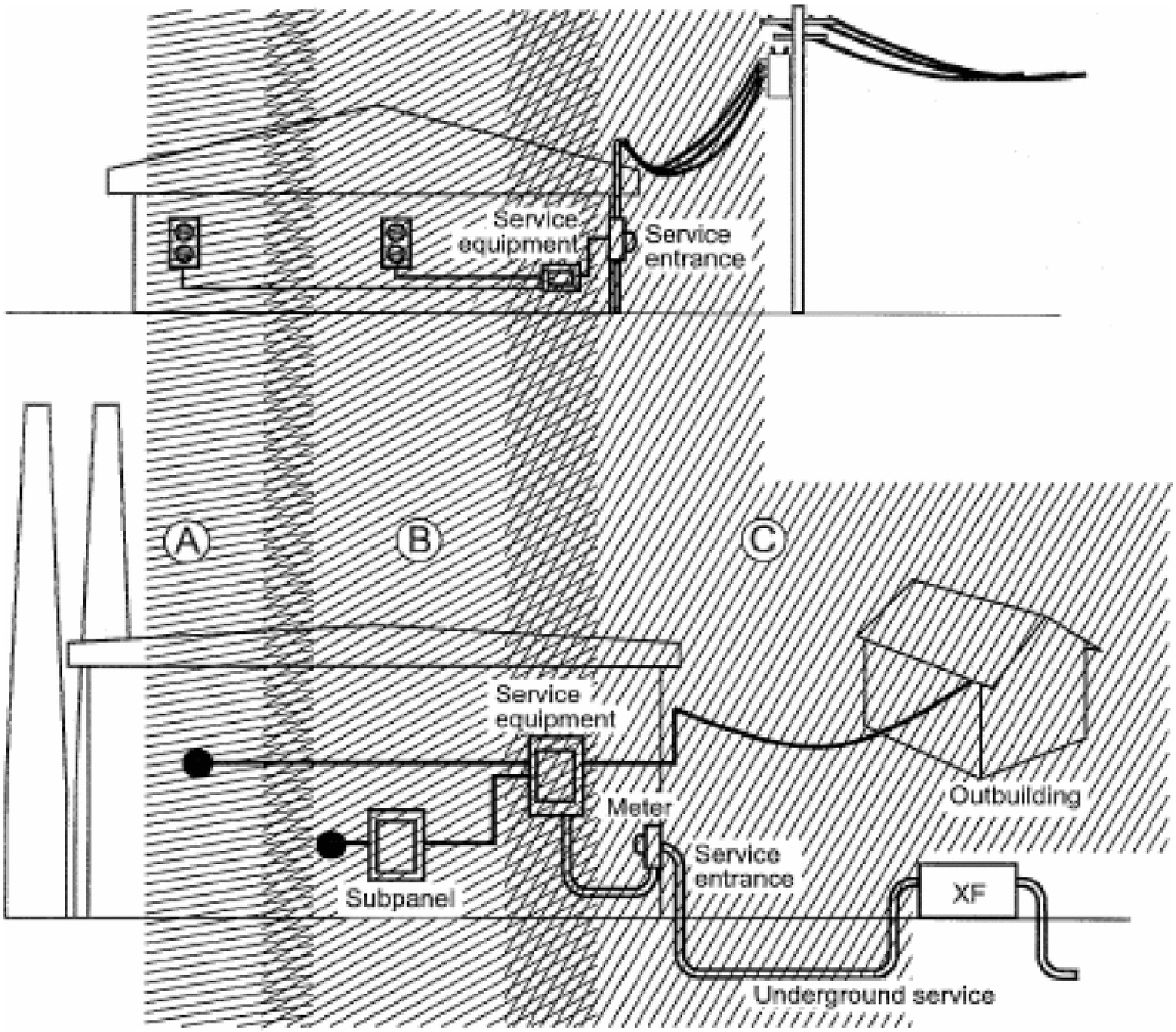


Figure 3.1. Location Category Illustration

3.1.2.4 *Relationships of SPD Location Categories to ITS Equipment*

Most ITS installations are not installed in building-size structures, and thus the location categories described above do not directly apply to ITS equipment installations. However, the C and B categories can be applied to the AC service protection for ITS systems. Meters and underground service connections are essentially the same as Category C locations in the IEEE standards. Category B locations can only be seen to be equivalent to the locations on the low voltage side of transformers that provide the power to the ITS equipment, assuming the transformers are located at the service entrance to the ITS cabinet.

At first glance, it would appear that Category A locations are equivalent to SPD installations within the cabinets and structures of the ITS installation. However, many of the SPDs within the ITS cabinets and equipment are connected to conductors (power or signal) that either extend a significant distance within the structure (e.g., to the top of a light pole) or extend outside the main cabinet through or to other structures (e.g., variable message signs). Therefore, many of these SPD locations would be more closely analogous to Category C locations.

3.1.3 Waveforms for Surge Testing

In addition to characterization of electrical surge environment and location categories, IEEE has developed three documents to provide the guidance regarding waveform representation, their amplitudes, and testing procedures for SPDs testing. The documents are as follows:

1. IEEE Standard C62.41.2-2002 – "IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits"
2. IEEE Standard C62.45-2002 – "IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V and Less) AC Power Circuits"
3. IEEE Standard C62.62-2000 – "IEEE Standard Test Specification for Surge-Protective Devices for Low-Voltage AC Power Circuits"

3.1.3.1 *Standard Surge Testing Waveforms*

There are two types of waveforms for surge testing based on surge environment; one to simulate the switching surges and other to simulate the lightning surges.

100 kHz Ring Waveform

This waveform is intended to represent the switching surges and oscillatory phenomenon related to inductive effects of lightning strikes. The 100 kHz ring waveform is defined as shown in Figure 3.2. Note that this waveform has no defined current waveform. This waveform is not intended to provide high-energy stress of the SPD, but rather to test the response of the SPD to a more rapid voltage change. Tests using this waveform are designed to identify the susceptibility of the protected equipment to upset during fast transients rather than the vulnerability of the SPD (and protected equipment) to damage.

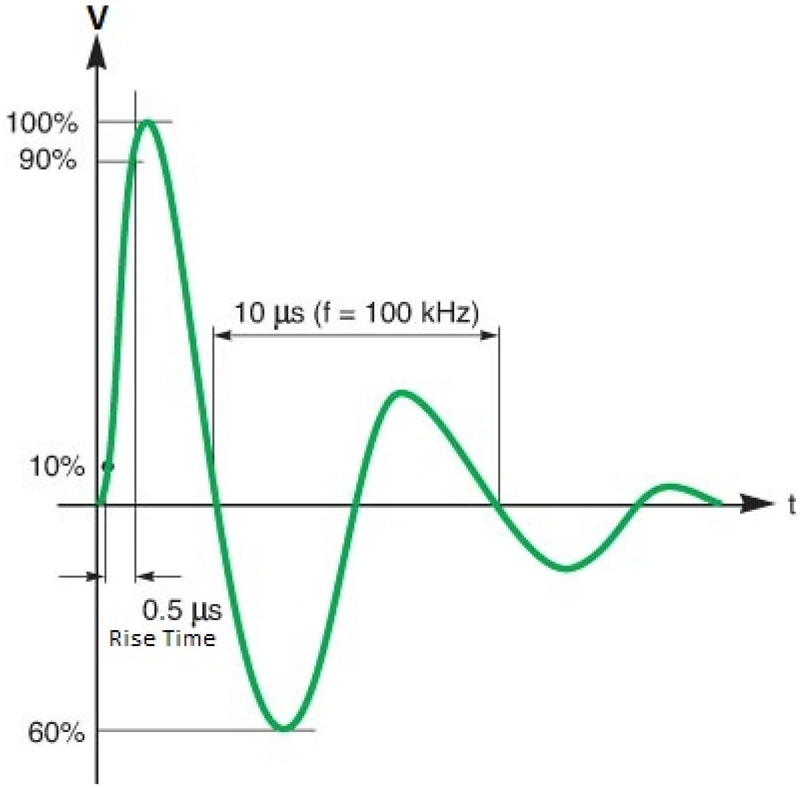


Figure 3.2. 100 kHz Ring Wave (Open Circuit Voltage)

Combination Waveform (1.2/50 µs voltage / 8/20 µs current)

To represent the lightning or impulsive surge phenomenon, the combination waveform is used. The combination wave test is described by the following characteristics:

- Open-circuit voltage with a rise or front time of 1.2 µs.
- A decay time to reach 50% of maximum peak open-circuit voltage is 50 µs.
- Short-circuit current rise or front time of 8 µs.
- A decay time to reach 50% of maximum peak short-circuit current is 20 µs.

The open-circuit voltage and short-circuit current waveforms for the combination waveform are shown in Figures 3.3 and 3.4, respectively. This waveform is intended to provide high-energy stress testing of the SPD to determine the vulnerability of the SPD to damage from lightning surges.

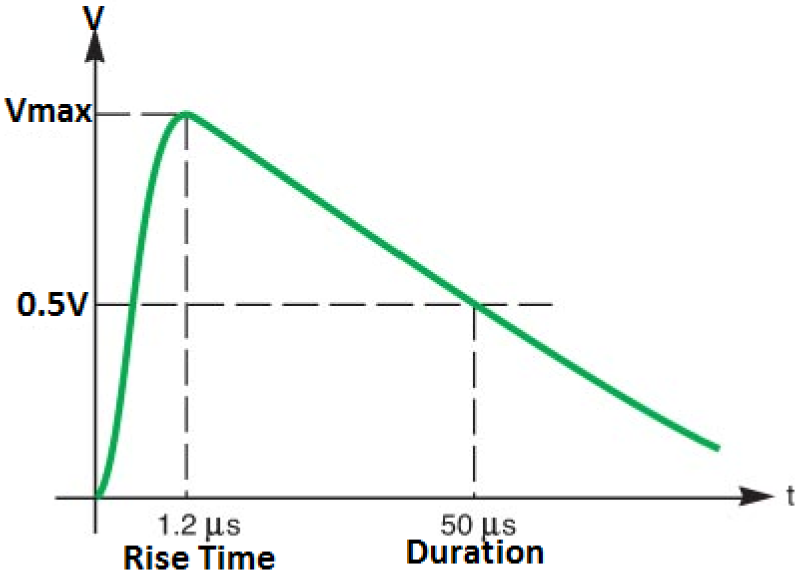


Figure 3.3. 1.2/50 microseconds Combination Wave (Open Circuit Voltage)

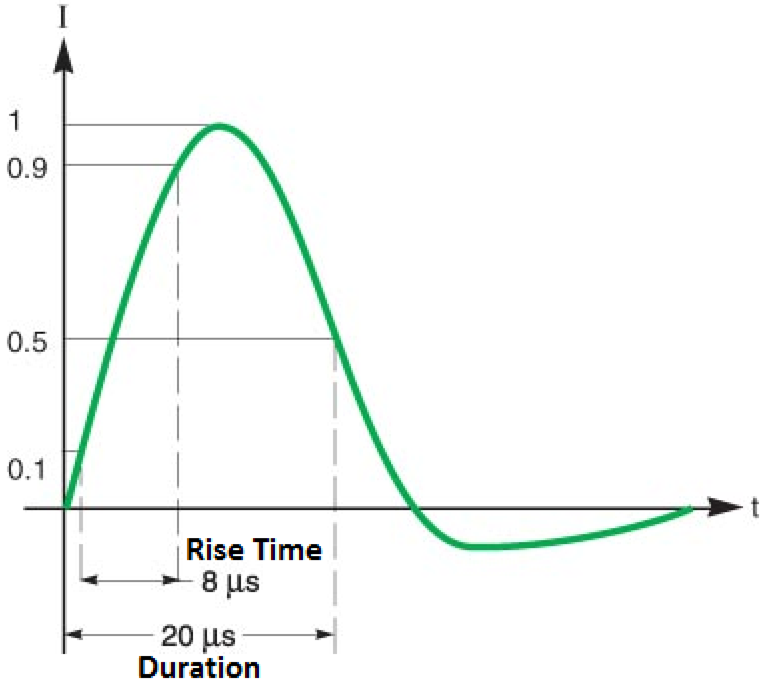


Figure 3.4. 8/20 microseconds Combination Wave (Short Circuit Current)

Surge Tests and Recommended Amplitudes by Location Category

The IEEE standards C62.41.2-2002 and C62.45-2002 provide a set of recommended tests and amplitudes by location category for the Scenario I surge environment. These are not mandatory requirements but rather a set of recommendations that can be modified to adapt to the specific environment and requirements. These values have been provided as guidance and uniformity for testing SPDs.

A summary of the recommended standard tests including the recommended peak voltages and currents is provided in Table 3.1. The Ring Waveform does not specifically specify peak short circuit currents; however, these recommendations do include peak currents for uniformity in testing. Also, the Ring Waveform is optional for Category C locations. Finally, the recommended peak voltages and currents for Category C locations is defined for "Low" and "High" lightning exposure levels. The terms "Low" and "High" are qualitative and not defined precisely.

Location Category	**Combination Waveform**		**Ring Waveform**	
	Peak Voltage (kV)	Peak Current (kA)	Peak Voltage (kV)	Peak Current (kA)
A	6	0.5	6	0.2
B	6	3	6	0.5
C Low	6	3	6 (optional)	**
C High	10	10	6 (optional)	**

** - Not specified

Table 3.1. Table of Recommended SPD Tests by Location Category

Most ITS equipment installations do not have high exposure to switching activity (more common in industrial facilities), but a greater exposure to high lightning activity making the performance of the SPD with respect to the combination waveform of greater importance (IEEE Std. C62.41.2-2002, pg. 20).

3.1.3.2 *Optional Surge Waveforms*

There are two optional surge waveforms for Scenario I lightning surges included in the IEEE standards C62.41.2-2002 and C62.45-2002. These optional waveforms are intended for specific applications.

The Electrical Fast Transient (EFT) Burst

The EFT Burst waveform is designed to test the immunity of the equipment to rapid electrical interference, particularly on the power supply. The EFT Burst waveform consists of series of individual voltage pulses applied at a rate of 2.5 kHz or 5 kHz (depending on peak voltage) for approximately 15 msec. Each pulse has a rise time of 5 ns and duration (to 50% peak) of 15 ns. The bursts are repeated every 300 ms. The amplitude of the pulses is determined by application and typically ranges from 1 kV to 3 kV.

Due to the very short duration of these pulses they do not contain a large amount of energy. Thus these tests are not generally physically damaging to the SPDs or the protected equipment.

However, many available SPDs do not have a short enough response time to effectively dampen or block the EFT pulse from reaching the protected equipment. The EFT Burst waveform thus are useful for determining if the protected equipment's operation will be interrupted by fast transient voltages.

The 10/1000 µs Long Wave

The 10/1000 µs Long Wave was designed to provide an energy stress to the SPD. This waveform is defined as a pulse with a rise time of approximately 10 µs and a duration (to 50% peak) of 1000 µs. This test pulse is to be added to the AC power lines at an amplitude up to 1.3 times the peak AC voltage. This waveform generally tests the SPD's (or other equipment's) high energy-delivery capability and not the durability of the SPD to lightning surges.

Neither of these optional surge waveforms are useful for testing the resilience and durability of SPDs used in ITS installations.

3.1.3.3 *Alternatives to the 1.2/50 µs Voltage / 8/20 µs Current Combination Waveform*

The 1.2/50 µs voltage / 8/20 µs current standard Combination Waveform, currently standard in North America) is not the only waveform used to test SPDs. For example, the current waveform required by the IEC standards (IEC 61643-11) and used in Europe includes a 10 µs rise time and duration of 350 µs (10/350 µs current). This waveform has a 17 times higher charge delivered than the 8/20 µs waveform in the IEEE standards. There exists a number of references concerning lightning stroke waveforms including measurements and analyses. Section 6 of the IEEE standard C62.41.1 provides a summary of tests and measurements used in defining the combination waveform. However, the 10/350 µs waveform still is included in the IEC 61643-11 (which replaced the IEC 61643-1 in 2011). The following is a comparison of the development and justifications for 8/20 µs and the 10/350 µs current waveforms. The primary source for this comparison is a summary paper by Bruce Glushakow and Dion Neri, "A call to standardize the waveforms used to test SPDs," *International Conference on Lightning Protection*, Avignon France 13-16 Sept. 2004.

The 10/350 µs waveform in the IEC standard was based on studies conducted in 1975 and 1980 which measured the characteristics of direct lightning flashes, but did not include measurements on the lightning surges experienced by AC power circuits. There have been several criticisms of these studies and the conclusions that were extrapolated from the measurements conducted. For example, the measurements conducted in 1975 were initially identified as measurements on the less common positive lightning strokes, but the author of the study later determined that the measurements were likely to have been on negative strokes. The author also commented that the positive strokes recorded "do not have enough common features to produce an acceptable mean current shape." The 1980 study was focused on the incidence of lightning and the front characteristics of the lightning strokes, and did not evaluate the duration of the strokes.

There are more recent studies which have measured the duration of direct lightning strikes. These studies tend to support the 8/20 µs current waveform over the 10/350 µs waveform. Below is a summary of these studies quoted from the paper by Glushakow and Neri:

1. *A 5-year study by the Korea Electrical Power Corporation used an LPATS manufactured by Atmospheric Research Systems of USA. Their results found 95% of measured strokes to have a time-to-half-peak of less than 22 μs. The average time to half peak was 10.82 μs.*
2. *A 3-year study in Japan found the mean value of the time to half peak of all lightning flashes recorded to be 50 μs and the longest duration 80-100 μs to occur in only 10% of all lightning flashes.*
3. *The released observations of the FORTE SATELLITE (a low-earth orbit satellite carrying radio wave and optical instruments for the study of lightning) have corroborated the Japanese findings.*
4. *The Western region offices of the US National Weather Service acquired lightning data through a cooperative agreement with the Bureau of Land Management in a 15-year study that ended in 1997. The results of that study showed that the nominal duration of a lightning stroke was 20 to 50 μs.*
5. *A paper presented at the 10th International Symposium on High Voltage Engineering held in Montreal, Canada in 1997 reported on a seven-year study of lightning phenomena conducted by Japanese CRIEPI. Among the results was the fact that the measured pulse widths of lightning lay between 12 and 20 μs.*
6. *The conclusion of the IEEE, based on a broad and exhaustive survey of testing waveforms and procedures, was issued in the IEEE Trilogy released this past year: "The two standard waveforms recommended by IEEE Std C62.41.2-2002 are the 100 kHz Ring Wave and the 1.2/50 μs, 8/20 μs Combination Wave (the latter involving two waveforms one for voltage and the other for current).*

Another summary and analysis of the 8/20 μs versus the 10/350 μs current waveforms was presented in a paper by Andreas Beutel and John Van Coller, "Issues Relating to Long and Short Duration Impulse Current Waveforms," *Proceedings of the XIVth International Symposium on High Voltage Engineering*, Tsinghua University, Beijing, China, August 25-29, 2005. In this paper the authors noted that the 10/350 μs current waveform was specified in current IEC standards only for SPDs that may be exposed to direct lightning strikes; the 8/20 μs current and the combination waveforms were specified for the protection from indirect lightning surges. This paper included results for some studies that measured direct lightning surges with durations up to 1200 μs. However, most of the studies measuring direct lightning strokes and power line surges recorded current waveform durations much closer to the 8/20 μs current waveform. The authors concluded that most of the studies supported 8/20 μs waveform, there was some evidence to support the 10/350 μs waveform for some cases, and the 8/20 μs waveform has been successfully used for testing for a longer time than the 10/350 μs waveform.

3.1.4 Conclusions and Recommendations for SPD Testing Waveform

A review of the existing waveforms and standards for testing SPDs was conducted. The review included IEEE and IEC standards, and technical literature on the topic. The results and recommendations were applied to SPDs installed in typical ITS field installations. The conclusions of this review include the following:

1. The SPDs located in ITS installations are most closely analogous to the Category C location defined in the IEEE standards C62.41.1-2002, C62.41.2-2002 and C62.45-2002. Many of the SPDs used to protect the ITS equipment are connected to signal or power wires that extend outside the cabinets and structures of the ITS installation.
2. The SPDs for use in the ITS installations should be selected primarily for their capability to protect the electronic equipment from indirect lightning strikes (analogous to the Scenario I defined in these IEEE standards). Direct lightning strike surges are relatively rare (Scenario II) compared to surges from more distant lightning strikes. The lightning terminals and grounding cables are a more effective method to mitigate or reduce the effects of direct lightning strikes.
3. The combination waveform (1.2/50 μs voltage / 8/20 μs current) is an effective standard waveform for testing the resilience of ITS SPDs to damage from lightning surges. There is a long history of the effective use of this waveform and significant evidence that this waveform relatively closely approximates the majority of the lightning surges expected.
4. The 100 kHz standard ring wave can optionally be used to identify if the transient surge voltages will upset or temporarily disrupt the operation of the protected equipment. This type of test is important if the operation of the equipment must be maintained for the safety purposes (e.g., traffic signals), but is not as important for ITS installations and equipment. NEMA TS2 standards currently includes testing procedures for transient immunity of traffic control equipment.

Recommendations:

I. The use of the standard combination waveform (1.2/50 μs voltage / 8/20 μs current) to evaluate and approve the performance of SPDs used in ITS installation in Florida shall be continued.

II. The peak current and voltage used for testing the SPDs shall be determined by the installation location and exposure to current surges due to lightning strikes. In no case should the SPD be tested at a peak voltage or current that exceeds the rating of the SPD. If the SPD is rated to withstand a current greater than the maximum that can be provided with existing surge generator, then the SPD can be tested using multiple surges at the maximum capability of the surge generator.

3.2 Recommended Lab Environment/Equipment and Testing Procedures

> *A report that identifies lab environment/equipment and testing procedures recommended for the testing of the Department's Approved Product List (APL) equipment (protected with APL SPDs) and subjected to the criteria recommended in Section 3.1. The report must recommend commercially available tools and test equipment that can be used to perform industry-standard SPD performance evaluations (identifying purpose, make, model, specific configuration options, and cost).*

In Section 3.6, it was determined that the standard IEEE 1.2/50 μs voltage / 8/20 μs current waveform was the most appropriate waveform to use in testing the SPDs for use in ITS installations. This section will identify the equipment needed to test the performance of SPDs currently in or requested to be added to the FDOT Approved Product List. In addition, recommended testing procedures will be recommended for use in approving SPD for inclusion in the APL.

3.2.1 Tests and Measurements of SPD Performance

To determine if an SPD is appropriate for use there are 2 types of tests that must be conducted. First, tests must be conducted to determine if the SPD will protect the equipment from damage from typical lightning-induced surges. These tests include the measurement of the let-through voltage parameters of an SPD experiencing a surge event. Secondly, the SPD also needs to be tested to determine resilience of the SPD to the high number of lightning surges expected in ITS equipment installed along roadways in Florida.

3.2.1.1 *Measuring Let-Through Voltage Parameters*

The primary parameters or specifications that relate to an SPD's ability to protect equipment from damage due to lightning surges are the parameters of the output or let-through voltage waveform. Figure 3.5 depicts a simplified SPD let-through waveform including some of the pertinent parameters.

Pertinent Let-Through Voltage Parameters

> DC Spark-Over Voltage:
> This terminology is often associated with gas tube or similar SPD devices. However in general terms this refers to the voltage at which the SPD responds to an over-voltage event. The minimum DC spark-over voltage must be greater than the maximum operating voltage (with some margin for incidental variations in the operating voltage) to avoid activation of the SPD .
>
> Response Time:
> This is the time from when the input voltage exceed the DC spark-over voltage until the SPD's output voltage is brought back below the DC spark-over voltage. This parameter affects the let-through energy allowed prior to the SPD suppressing the output voltage to a safe level. This is specified for many SPDs but the usefulness of this parameter is

considered by some as of less value than the crest value parameter. In addition, the response of an SPD to the front of a voltage waveform depends on the rate-of-rise of the incident voltage, the impedance of the surge source and connecting wiring, the effects of protective device reactance, and the response behavior of conducting mechanisms within active suppression elements. Thus the response time of an SPD tested may differ significantly from the response time when the SPD is installed in the field.

<u>Crest Value (Peak):</u>
The maximum voltage at the output of the SPD during (typically at the start of) a transient voltage event. This value is dependent not only on the response time of the SPD but also on the slope of the surge voltage waveform. Therefore, the crest value is typically dependent on the magnitude of the surge voltage waveform. If specified, the crest value is typically specified at particular input voltage (or current) levels. A lower crest value provides better protection from failure, especially for low-voltage devices such as communications, video or signaling electronics.

<u>Clamping Voltage (Suppressed Voltage Rating or Transient Suppression Voltage):</u>
The clamping voltage is also known as the let-through voltage, the Suppressed Voltage Rating (SVR in IEEE Std C62.72-2007) or the Transient Suppression Voltage (in UL 1449). Transient suppression voltage is defined in UL 1449 as "The maximum peak voltage occurring within 100 microseconds after the application of the test wave." Essentially, it is the maximum amplitude of the voltage after the SPD has responded to the input transient and limited the output voltage to the protected device. For an SPD used on power (AC or DC) systems, the clamping voltage should be above the maximum (including normal variations) operating voltage of the power supply as shown in Figure 3.5. Clamping at a voltage below the power supply's maximum operating voltage can cause the SPD to overheat and be damaged. For communication, data, video and similar signals, the clamping voltage must be below the maximum rated input voltage of the devices to provide adequate protection of the devices, but can be below the operating signal voltages since the power in the signals is not sufficient to cause the SPD to overheat.

Measuring the Let-Through Voltage Parameters

To measure the let-through voltage parameters for an SPD a standard IEEE surge waveform (1.2/50 μs voltage / 8/20 μs current) is applied to the input of the SPD and the voltage at the output of the SPD is captured using an oscilloscope. The oscilloscope used must be capable of capturing transient (single) waveforms, and have the bandwidth and voltage range necessary to accurately capture the output waveform. There are many off-the-shelf digital oscilloscopes available with maximum input voltages of 300V or more, and bandwidths of at least 100 MHz that can be used to capture the let-through waveform. Once the waveform has been captured by the digital oscilloscope the parameters can be measured using standard functions on the oscilloscope, or the waveform data can be exported to a computer to more accurately perform the parameter measurements.

Each of the let-through voltage parameters should be measured at multiple surge currents up to the maximum rated current of the SPD. The results of these measurements shall be compared with the specifications of the SPD and the required specifications determined by the FDOT for the particular application of the SPD.

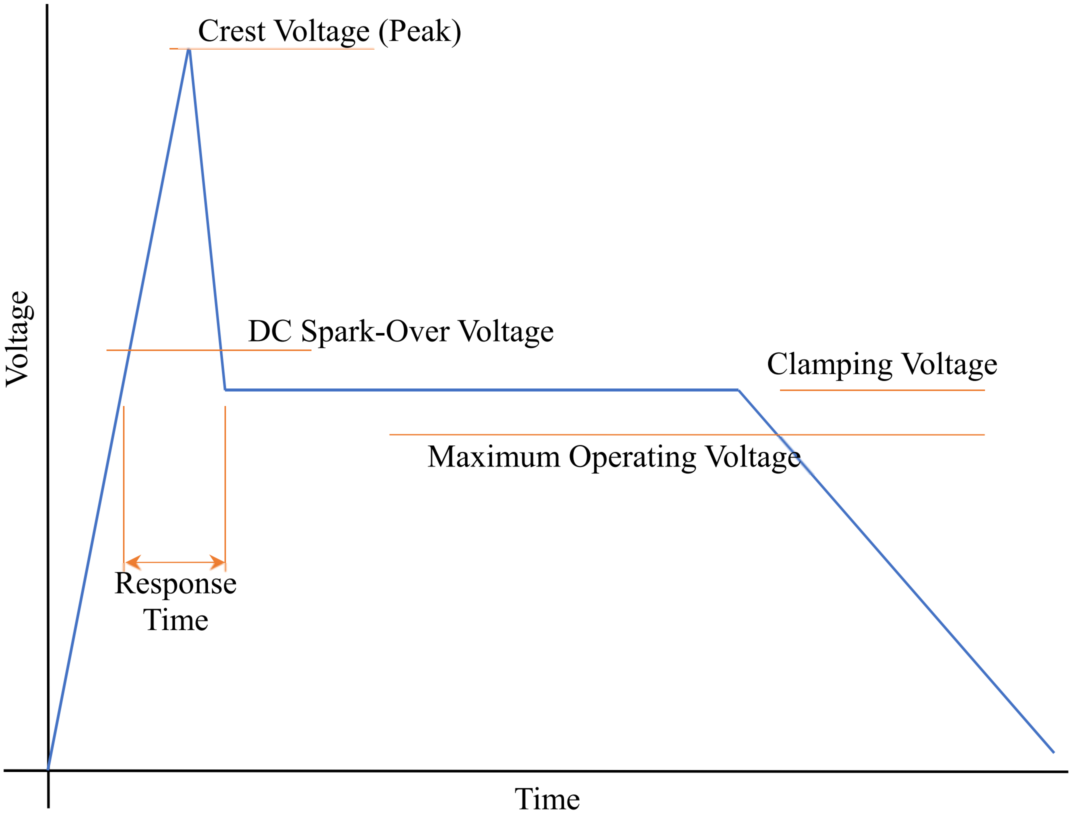


Figure 3.5. Simplified SPD Let-Through Waveform

3.2.1.2 *Testing the Resilience of the SPD*

In the lightning environment of Florida an SPD must be capable of enduring multiple lightning surges while still providing the required protection for the equipment. Therefore, the testing of an SPD for resilience is a two-part process. The SPD must be tested first to determine if the SPD fails or suffers physical damage after multiple surge events are applied to the SPD. Second, the let-through voltage parameters must be monitored to determine if the required specifications of the SPD continue to be met by the SPD as the number and magnitude of the surges applied to the SPD increase.

The IEEE, NEMA and UL standards reviewed do not directly specify the number of surges that an SPD must be required to endure. The number of lightning strikes varies greatly depending on geographic location and thus the resilience required of the SPDs can vary considerably. The State of Florida has the highest rates of lightning flashes per kilometer in the country and thus the SPDs used in Florida must be capable of enduring large numbers of surges to keep maintenance costs down.

Determining an appropriate Florida FDOT specification for the number and magnitude of surges that the SPDs are required to endure will require testing and monitoring the resilience of SPDs installed over time. SPDs currently in use can be tested to determine their resilience to various magnitudes (currents) of surges. The performance of the SPDs installed at sites around Florida can then be monitored to determine how long the SPDs continue to protect the equipment effectively. If an SPD for a particular application is found to be less resilient or reliable, then a replacement SPD, tested to have greater resilience, can be identified and the minimum resilience specification modified accordingly. Over a period of time, appropriate specifications can be defined and used to approve SPDs for use across Florida.

A field test[3] was conducted from 2005 to 2014 to count and measure the magnitude of lightning-induced surges through the in-pavement sensors (piezoelectric axle sensors and loop detectors) at FDOT telemetered traffic monitoring sites (TTMS) in central Florida. These field tests found there to be an average of 2–3 surge events per day through each in-pavement sensor, with an average surge current of about 200 amps. The peak surge current detected was over 8,000 amps, and the 99th percentile of the lightning surge currents was 1,000 amps. The tests also revealed that some moderate to high surge events consisted of multiple surge peaks within a period sometimes over 0.5 seconds. Based on these field tests, it was recommended that SPDs for the in-pavement sensors have a peak current capability of 10–20 kA and that the SPD be capable of enduring at least 5,000 surges with a peak current of 6 kA. This recommendation is a good starting point for determining an appropriate Florida FDOT specification for the number and magnitude of surges that the SPDs are required to endure.

3.2.2 Lab Environment and Test Equipment Required

The testing of SPDs can be safely conducted in a typical indoor laboratory environment using benchtop equipment. Extreme caution should be exercised by those conducting the tests since the voltages and current used in testing are very dangerous and potentially lethal. The tests should be conducted in an area free of clutter, liquids, extraneous wires or other material which can potentially conduct the electric energy. While the test equipment is active and generating the test waveforms, all lab personnel should avoid contact with the test equipment and the SPD under test until the tests are completed or the equipment is placed in a safe mode.

There are two primary pieces of laboratory test equipment required to test SPDs. The first is a lightning surge generator capable of generating the IEEE standard 1.2/50 μs voltage / 8/20 μs current waveform. The second piece of equipment needed is an oscilloscope to measure the let-through voltage waveform of an SPD under test.

The lightning surge generator needs to be capable of generating waveforms with peaks of multiple kV and kA range. For safety, the generator should be equipped with a test cabinet or enclosure to insulate the test personnel from the dangerous pulses and to contain protect personnel from projectiles generator should an SPD or component explode.

---

[3] Harvey, B.A., "Long-Term Field Study of Lightning Surges Through Traffic Monitoring In-Pavement Sensors," *IEEE Transactions on Industry Applications*, Vol. 51, No. 4, July/August 2015, pp. 2797-2803.

The lightning surge generator recommended is the MIG0606 Current Tester fitted with the TC-MIG24ED test cabinet (see Figure 3.6). This equipment is commercially available from EMC Partner AG (https://www.emc-partner.com/). This generator is designed specifically for testing SPDs for low-voltage (< 1 kV) applications. The specifications of the surge generator are

- Waveform: IEEE 1.2/50 μs voltage, 8/20 μs current
- Peak Open-Circuit (oc) Voltage = 6 kV
- Peak Short-Circuit (sc) Current = 6 kA
- Current Range = 0.25 to 6 kA in 1 Amp steps
- Polarity = positive, negative or alternating
- Internal Resistance / Source Impedance = 1 Ohms

The generator also can be programmed to execute a series of surges to test the long-term resilience and performance of SPDs.

Figure 3.6. MIG0606 Surge Generator with TC-MIG24ED Cabinet

The oscilloscope used for the SPD testing needs to have the bandwidth and voltage range required to properly record the let-through voltage of an SPD under test. To measure the rapid transients associated with the lightning surges it is recommend that the bandwidth of the oscilloscope be at least 100 MHz. Also, it should be able to measure voltages up to at least 300 V with a high-impedance probe (~1 MΩ). For proper triggering to capture a single surge event, the oscilloscope will require 2 or more inputs. Finally, in order to document the measurement and the waveforms, the oscilloscope will need to be a digital oscilloscope with a port for storing the recorded waveform onto a digital memory storage device (SD card, USB drive, etc.).

The recommended oscilloscope for the SPD testing is the Tektronix MDO3024 Mixed Domain Oscilloscope (see Figure 3.7). This oscilloscope has the following specifications:

- Analog Bandwidth = 200 MHz
- Number of Channels = 4
- Sample Rate = 2.5 GS/s
- Maximum Input Voltage = 300 Vrms (using 10:1 standard probe)
- Input Impedance = 1 MΩ, 50 Ω or 75 Ω
- 2 USB ports for mass storage devices, printing and control

The MDO3024 has multiple options including 16 digital inputs, arbitrary function generator and a spectrum analyzer making it a flexible instrument that is useful for other potential measurements and testing.

Figure 3.7. Tektronix MDO3024 Mixed Signal Oscilloscope

A MIG0606 generator with the TC-MIG24ED cabinet had already been acquired by the FDOT for use in previous projects. Therefore the existing generator only required updated calibration for use in this current effort.

After obtaining approval from the FDOT, the MDO3024 oscilloscope was purchased and has been received. The oscilloscope purchased included the MDO3AFG arbitrary function generator and the MDO3MSO 16-channel digital measurement options. The purchase included standard 10:1 analog signal probes and the digital signal probes.

3.2.3 Recommended Test Procedures

The recommended test procedures consist of two phases: 1) initial performance verification and 2) resilience testing.

***** WARNING***** These tests involve potentially lethal voltages and currents and extreme caution is advised. For safest operation, the test equipment, SPD and associated wiring should not be touched while the surge generator is charging and executing a surge waveform. Also, the test area must be clear of all non-essential equipment and material (especially wire). Press the red safety cut-off on the surge generator before touching any of the test setup.

3.2.3.1 *Initial Performance Tests (Phase 1)*

The initial performance tests are designed to determine the performance and verify the specifications of the SPDs at multiple surge magnitudes (both positive and negative polarity). For these the output voltage waveform of the SPD will be recorded on the oscilloscope and the response time, crest voltage and clamping voltage will be determined.

Steps:

1. Turn on the oscilloscope and the surge generator, and verify that the Emergency Stop button on the surge generator is activated (pressed). The green light, "OPEN", will be on if the Emergency Stop button is activated and it is safe to open the safety cabinet. See Figure 3.8.

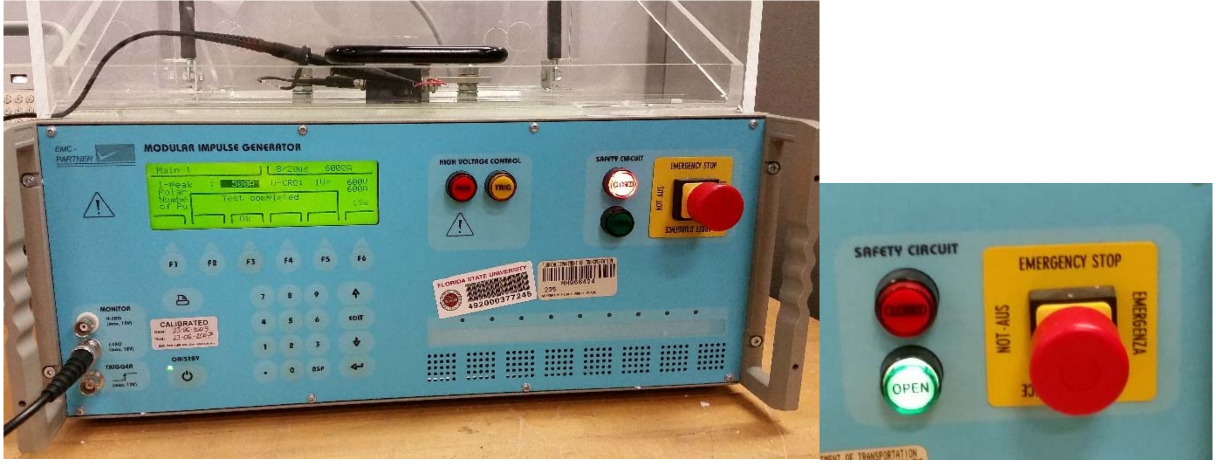


Figure 3.8. Surge Generator and Emergency Stop (button presses with green light on)

2. Place the SPD under test inside the safety cabinet and connect the surge generator terminals to the input of the SPD. Connecting wires should be 16 AWG or larger (14 AWG or 12 AWG), and the wires should be as short as practical and free of unnecessary loops.
3. Connect the oscilloscope probe to the output of the SPD. This will require the end of the oscilloscope probe to be placed within the safety cabinet of the surge generator. Use the 10:1 probes provided with the oscilloscope. See Figure 3.9.

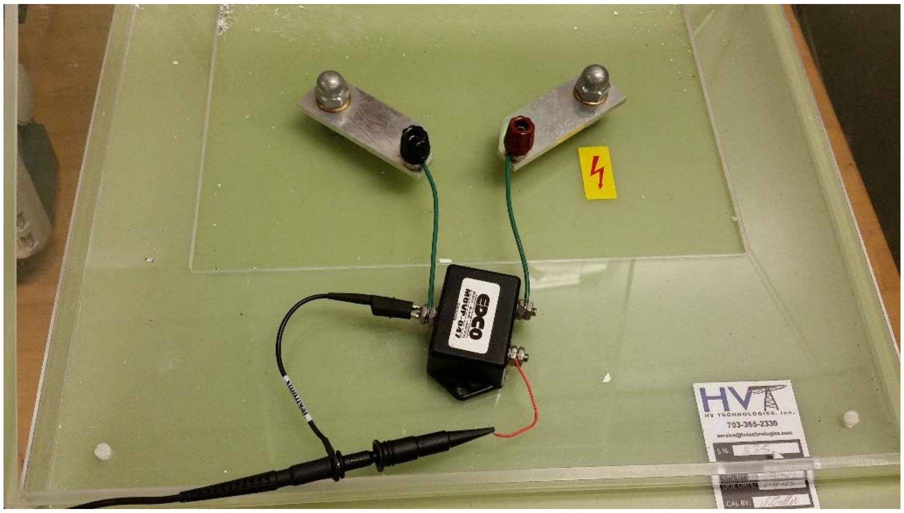


Figure 3.9. SPD Connected to the Surge Generator with Oscilloscope Probes

4. Close the safety cabinet on the surge generator. Be careful not to crimp or damage the oscilloscope probe wire.
5. Adjust the time base on the oscilloscope to ~4 μs per division. Set the vertical scale to display the expected peak voltage. Set the mode on the oscilloscope to single to capture

one surge. The oscilloscope can be triggered using the output waveform of the SPD, the voltage or current outputs of the surge generator, or the trigger output of the surge generator. Also, the Horizontal position knob can be used to offset the trigger offset time to approximately 1 division from the left side of the display.

6. Set the surge generator to produce a single positive 500 A surge pulse. Pull the Emergency Stop button (red “CLOSED” light illuminates) to make the surge generator active. Start the test by pressing the red “RUN” button on the surge generator. ***CAUTION*** The generator will now charge internal capacitors and then trigger a surge. **Do not touch the equipment or wires until the surge is complete and the Emergency Stop button has been pressed.** Figure 3.10 depicts the test equipment set-up with an example capture SPD output on the oscilloscope.

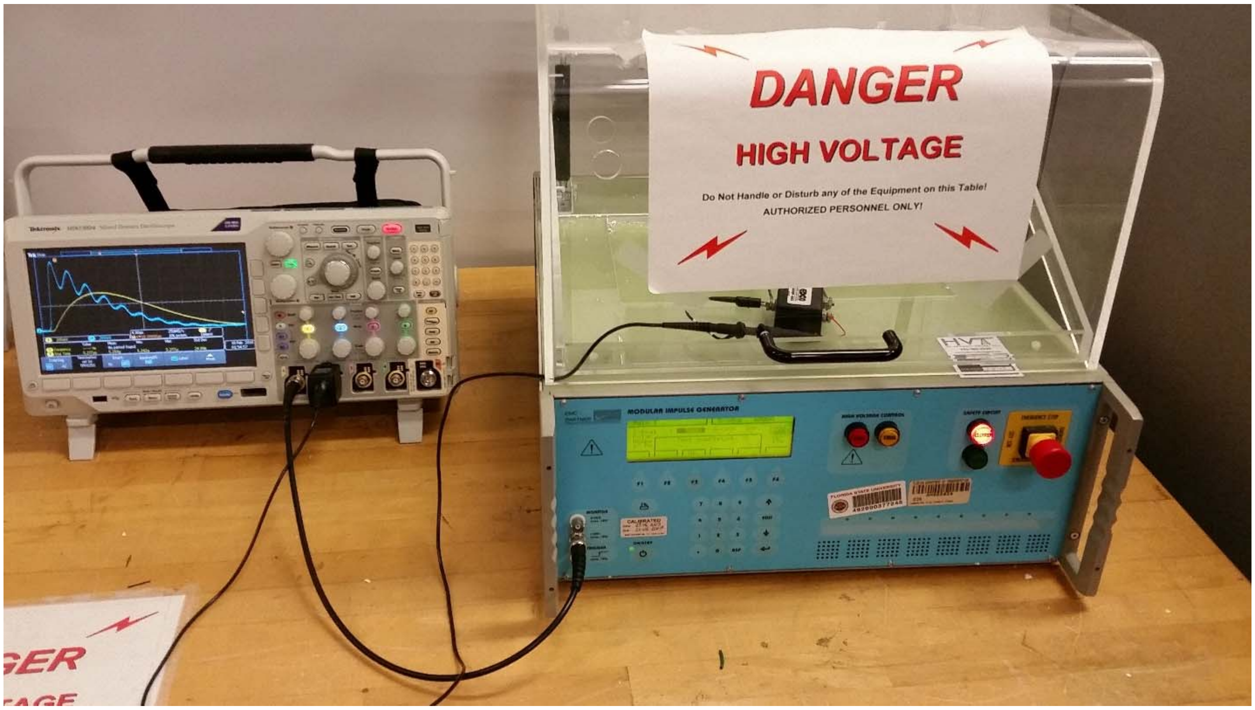


Figure 3.10. Surge Test Equipment Setup with SPD Output Displayed on the Oscilloscope
Note: The surge current waveform (scaled 1V per 500 A)
was used for triggering and also displayed in yellow.

7. The SPD let-through voltage parameters are then determined from the oscilloscope display or the data downloaded from the oscilloscope.
8. Repeat Steps 1 – 7 for multiple surge magnitudes (up to the specified maximum surge current) and both positive and negative polarity.

The output voltage waveform of most SPDs is not as simple as the waveform shown in Figure 3.5. Most SPDs are constructed using multiple components such as gas tubes, varistors, inductors and resistors. The output waveform of an SPD may even appear to oscillate as shown (blue waveform) on the oscilloscope in Figure 3.10. Also, the surge current magnitude setting on the surge generator refers to the “short circuit” surge current peak. The actual peak surge current from the generator depend on the impedance of the SPD.

3.2.3.2 *SPD Resilience Testing Procedures (Phase 2)*

The resilience tests are designed to provide a consistent measure of the ability of an SPD to protect the electronic equipment from multiple (or many) lightning surges. There is no standard for resilience testing and thus the surge current and number of surges used in the procedure recommended here are a starting point that can be refined as the installed performance of tested SPDs is monitored over time.

The SPD tests are to be performed on SPDs that have passed the initial performance test described in Section 3.2.3.1. The surge current initially recommended for this test is 6,000 A and the goal is to determine if the SPD remains functional within specifications after 5,000 surges have been applied by the surge generator. Polarity of the surges is not important The oscilloscope is generally not connected to the SPD during the resilience testing except when conducting performance testing periodically during the resilience tests.

Steps:

1. Turn on the surge generator, and verify that the Emergency Stop button on the surge generator is activated (pressed). The green light, “OPEN”, will be on if the Emergency Stop button is activated and it is safe to open the safety cabinet. See Figure 3.8.
2. Place the SPD under test inside the safety cabinet and connect the surge generator terminals to the input of the SPD. Connecting wires should be 16 AWG or larger (14 AWG or 12 AWG), and the wires should be as short as practical and free of unnecessary loops. Then close the safety cabinet of the surge generator. See Figure 3.9.
3. Set the surge generator to produce 500 positive 500 A surge pulses. Pull the Emergency Stop button (red “CLOSED” light illuminates) to make the surge generator active. Start the test by pressing the red “RUN” button on the surge generator. ***CAUTION*** The generator will now charge internal capacitors and then trigger a surge approximately every 30 seconds. **Do not touch the equipment or wires until the surge is complete and the Emergency Stop button has been pressed.**
4. If the SPD has no visible damage, then repeat the performance test for the SPD to determine if the SPD is still operating within the specifications of the unit. If the performance of the SPD is not operating within its specifications, the SPD has failed the resilience test.
5. Repeat steps 1 – 4 until a total of 5,000 surges have been applied to the SPD.

Note: The resilience tests should be conducted with supervision both for safety and to monitor the SPD. Catastrophic failure of an SPD can result in physical damage to the SPD including mechanical fracturing, melting components or smoke. Other evidence of catastrophic failure includes a significant increase in the sound (“popping”) from the SPD when a surge is applied; this is evidence of electronic arcing within the SPD.

3.2.4 Conclusions and Recommendations on Lab Environment/Equipment and Testing Procedures

The test equipment required to provide acceptance/performance testing of SPDs for use in ITS installations includes a surge generator and an oscilloscope. The specific equipment recommended for the SPD testing is

Surge Generator

MIG0606 Current Tester fitted with the TC-MIG24ED (see Figure 3.6) commercially available from EMC PARTNER AG (https://www.emc-partner.com/). The specifications of the surge generator are

- Waveform: IEEE 1.2/50 μs voltage, 8/20 μs current
- Peak Open-Circuit (oc) Voltage = 6 kV
- Peak Short-Circuit (sc) Current = 6 kA
- Current Range = 0.25 to 6 kA in 1 Amp steps
- Polarity = positive, negative or alternating
- Internal Resistance / Source Impedance = 1 Ohms
- Programmable to generate multiple surges.

Oscilloscope

Tektronix MDO3024 Mixed Domain Oscilloscope (see Figure 3.7). This oscilloscope has the following specifications:

- Analog Bandwidth = 200 MHz
- Number of Channels = 4
- Sample Rate = 2.5 GS/s
- Maximum Input Voltage = 300 Vrms (using 10:1 standard probe)
- Input Impedance = 1 MΩ, 50 Ω or 75 Ω
- 2 USB ports for mass storage devices, printing and control

The MDO3024 has multiple options including 16 digital inputs, arbitrary function generator and a spectrum analyzer making it a flexible instrument that is useful for other potential measurements and testing.

The recommended surge tests to be performed on each SPD include Initial Performance Tests (Section 3.2.3.1) of the voltage let-through waveform for the SPD, and SPD Resilience Tests (Section 3.2.3.2). The initial performance tests are used to measure response time, crest voltage and clamping voltage of the SPD at multiple surge current magnitudes and polarities. This test will determine the level of protection afforded by the SPD during a lightning surge event. The SPD resilience tests are designed to provide a consistent measure of the ability of an SPD to protect the electronic equipment from multiple (or many) lightning surges. For SPDs with a maximum rated surge current of 10 kA or greater, the initial recommended resilience tests consist of 6 kA surges applied to the SPD a total of 5,000 times.

All of the SPD tests recommended can be performed in a typical indoor benchtop laboratory environment. No special facilities are required. Special attention to safety is required as the surge generator can produce potentially lethal voltages and currents.

3.3 SPD Test Lab and SPD Test Results

> *A report that summarizes tests conducted and results using purchased equipment and recommended test procedures for each type of SPD specified in the Department's minimum specifications. All equipment purchased will be provided to the Department at the end of the project.*

In Task 1 of this project, the set of SPDs included in the FDOT Approved Product List (APL) was collected and listed with available specifications (Table 2.2). The SPDs in this APL can all be tested using the equipment specified and acquired as described in Section 3. Using the test procedures provided in Section 3, the specifications each of these SPDs can be verified up to a maximum surge current of 6 kA.

All of the equipment for the SPD Test Lab has been acquired and will be transferred to the FDOT laboratory at the conclusion of this project.

3.4 Site Monitoring Tools and Reporting Procedures

> *A report that identifies site monitoring tools and reporting procedures that would aid in the collection of data to help keep track of equipment failures and associated repair and/or replacement costs.*

During Task 1 of this project, a survey was conducted to determine the state of the practice in lightning protection in the State of Florida. There were two questions in this survey related to the monitoring tools and reporting procedures used in the FDOT individual districts. The related questions asked were:

1. Please provide monthly repair information (cost and/or # repairs) of ITS equipment for the past 5 years (if possible). ITS equipment can include traffic monitoring equipment, traffic cameras, DMS and lighting. While it is not generally possible to identify most lightning damage, the goal is to identify the increase in maintenance required during the peak lightning months.
2. Please estimate the average number of direct lightning strikes causing damage to ITS equipment in your district. Please provide examples of damage caused by direct lightning strikes to ITS equipment. For each example please try to provide information on the lightning protection equipment at the site, a list of the damages caused by the lightning and pictures of the lightning damage.

The responses to these questions provide insights into the current practices and procedures currently in use within the individual districts. The responses to question 5 came from only three of the FDOT districts and were primarily anecdotal examples. Included in the responses were pictures of obvious lightning surge damage and summaries of repairs of direct lightning strike damage. From the responses it appears that damage due to direct lightning strikes can cause significant damage, but the number of direct lightning strikes are relatively low compared to the overall maintenance required.

From the responses to question 1 it was evident that all of the responding districts used contractors to provide for and report ITS equipment failures. Additionally, each of the districts appeared to use distinct reporting methods and reports for tracking maintenance on their ITS equipment. In the following section, a summary of the responses to question 1 highlighting the apparent reporting tools used and the identification of lightning-related damage is presented.

3.4.1 Reporting Procedures in FDOT Districts

FDOT Districts 1, 2, 6 and 7 responded to question 1 in the survey with maintenance reports of various forms. This section summarizes the type of data received from each responding district and attempts to ascertain the methods used to identify lightning-related damage to ITS equipment.

District 1

District 1 sent a spreadsheet containing Work Order Summaries for the complete months starting in February 2010 and ending in July 2014. These summaries indicated the location and equipment type repaired but did not indicate the type or cause of the repair. The work order included a "Fix Category", but this information was typically blank or contained a generic description such as "General Task" or "Miscellaneous Correction."

There was no information in the spreadsheet that could be used to identify which, if any, of the work orders were the result of lightning damage. Therefore, the total number of work orders per month was determined in order to see if there were significantly more work orders during the peak summer lightning months (June–August). The results of this analysis indicated that on average there were about 26% more work orders during the summer lightning months than during the months when lightning is much less frequent (October–April).

District 2

District 2 provided a spreadsheet described as the "cost of lightning damage" covering the period of February 2013 through January 2014. The spreadsheet detailed the number and cost of devices that were replaced in the ITS equipment in District 2, and the cost of labor and vehicle rental to perform the maintenance. The data in the spreadsheet provided was gathered by the ITS maintenance contractor for District 2. Information on how the maintenance due to lightning damage was extracted from the total lightning damage was not provided.

Since only a single year of data was provided, it was difficult to identify trends in the data. The costs of labor and vehicles and the number of devices replaced appear to increase during the summer months and peak in September. The cost of devices, however, is highest in the months of September, February and April. The increase in costs in February, and April is due to the replacement of relatively few expensive MVDS devices. The higher device cost in September appears to be the direct result of an increase in the number of devices replaced. During the summer peak lightning months, the average number of devices replaced per month was 21. During the months with less frequent lightning (October-April) the average was 12 devices per month. Therefore, for this year, there were 75% more devices replaced during the summer peak lightning months.

District 6

District 6 provided monthly maintenance reports (PDF format) from their ITS Maintenance Service Contract with TransCore that covered the period from December 2011 through July 2014. These reports consisted of a list of "Tickets" containing entries including date and time the ticket was created, failure description, description of maintenance, model and Wisetrack Device # for parts replaced, and justification. The Description field was detailed enough that the work orders could be sorted (by the research team) into different categories. The categories used for the assessment of the work orders are described in the table in Table 3.2. The Justification field was used inconsistently and contained entries such as "Heavy Rain" and "After Hours" which did not help to identify whether or not the damage was caused by lightning.

By considering the total number of work orders (tickets) it was found that the number of work orders during the summer lightning months (June – August) were 54% higher than during the months when lightning is much less frequent (October – April). However, by considering only the work orders related to possible and likely lightning damage, there were approximately 62% more total work orders during the summer lightning months.

CATEGORY	DESCRIPTION
Visits no Damage	Maintenance visit not requiring replacement or repairs. Does not Include power company/AT&T issues, testing, or planned replacements. Examples: dirty dome, tightened cable, went to sight no problems.
Non-Lightning Damage	Had to repair or replace something, not from electrical issue. Example: hit by car, vandalism, ants, etc.
Possible Lightning Damage	Any problem that could be associated with lightning. Examples: resetting UPS/radios, having to replace PTZ cable, replacing of video SPD, etc.
Likely Lightning Damage	Problem almost certainly caused by lightning. Examples: tripped breakers, burnt SPD/ fuse, replacing of SPD for power source

Table 3.2. Table of Work Order Categories Used for Assessment

District 7

District 7 provided monthly maintenance reports (PDF format) from their ITS Maintenance Service Contract with TransCore that covered the period from June 2010 through August 2014. As was in the District 6 work order (ticket) reports, each work order had description that was detailed enough that the work orders could be sorted into different categories as listed in Table 3.2. The reports provided by District 7 listed activities in significant detail. Many of the reports appeared to be related to the same sites on the same day and were aggregated in this analysis as a single event to avoid duplication.

Considering the total work order averages, the average number work orders in the summer months (June – August) was approximately 40% higher than during the months when lightning is much less frequent (October – April). Considering only the work orders related to possible and likely lightning damage, the average number work orders per month for possible and likely lightning damage during the summer lightning months was 45.5% than during the months when lightning is much less frequent.

Note that over the timeframe of the data provided there were a total of 2953 work orders categorized. Of these, 2580 were categorized as Possible Lightning Damage and only 38 were categorized as Likely Lightning Damage.

3.4.2 Conclusions and Recommendations for Site Monitoring and Reporting Tools

The maintenance records data received from the FDOT districts indicate that damage to ITS equipment due to lightning can currently only be estimated based on the type of equipment damaged and descriptions of the circumstances provided by the technicians performing the maintenance. However, except in the case of extremely large lightning surges and direct lightning strikes, there is little or no visual evidence to determine if lightning caused the damage or if the damage was simple failure of electronic devices. Currently there is no standard or template used throughout Florida whereby the number and cost of lightning damage can be assessed statewide.

Therefore, it is recommended that a standard template for maintenance data entry be adopted to provide a standard system for monitoring and evaluating lightning damage to ITS equipment in Florida. This template should be required and included in the contract for all ITS maintenance contracts across the state, and the data should be stored in a standard data format to allow for aggregation and analysis of the data.

It is recommended that the standard template for ITS maintenance include the following:

1. Location of the site where the failure occurred
2. Date and time of the equipment failure
3. Likelihood that damage caused by lightning according to a standard scale such as:
    a. Very Likely Due to Lightning
        i. Visible evidence of large current surges
        ii. Damage to SPD, fuse/breaker tripped, or other obvious indications of lightning surges
        iii. Known significant lightning activity at the time of the failure
    b. Possibly Due to Lightning
        i. Electronic failures with no other cause evident
        ii. Cable or wires requiring replacement with no evidence of cause for failure
        iii. Resetting or restarting equipment
        iv. Lightning activity in the area at time of failure
    c. Unlikely to be Due to Lightning
        i. Damage not due to electrical problem (e.g., water intrusion, vehicle accident, vandalism, insect intrusion)
        ii. No or very little lightning at the time of the failure
    d. Maintenance, Not Damage-Related (i.e., regularly schedule maintenance)
        i. Regular maintenance (e.g., clean camera domes, calibration)
        ii. Upgrades or testing
        iii. Not related to ITS equipment
        iv. No maintenance required upon inspection
4. Equipment replaced as part of the repair including

    a. Type of equipment (e.g., SPD, communication, lighting, power, cable/wire)
    b. Description, model number
    c. Cost of the equipment
    d. Visual description of damaged or replaced equipment
5. Total cost of the maintenance required
    a. Equipment or components replaced
    b. Technician effort
    c. Vehicle or other equipment rental/costs
    d. Other related costs

In order to increase the compliance of technicians entering the data and to reduce reporting costs the maintenance template should be implemented with ease-of-use as the focus. There are a number of procedures and tactics that can be employed to facilitate the collection of the information in the template recommended above. These tactics include:

1. Use QR (or similar bar type) codes to label sites and major pieces of ITS equipment.
    a. Provides automatic entry into the template reducing typing.
    b. Simple database of ITS installation sites provide location and type of equipment at the location.
    c. Labeling equipment provides for automatic entry of type and cost.
2. Use radio buttons or drop-down boxes for rapid entry of selections (e.g., Likelihood of damage caused by lightning).
3. ITS maintenance contracts that require the use of a standardized data format (or output to a standard format) to facilitate the aggregation of the lightning damage data across the state.

Use of a standard ITS maintenance template and storage formats as recommended here has several benefits to the FDOT. These benefits include:

- The ability to better identify damage to ITS equipment caused by lightning and to aggregate the costs of lightning damage will provide the information needed to improve lightning protection measures and thereby reduce the cost of maintenance.
- Provide a historic record of lightning-related damage to validate the efficacy of changes to lightning protection equipment and installation methods.
- Allow for more intensive analysis of lightning damage by comparing records of lightning activity (available through public and commercial sources) with damage to more accurate identify lightning related damage.

3.5 Best Practices Nationally for Use of SPDs to Protect Similar Equipment

> *A report that identifies best practices nationally regarding the use of SPDs to protect similar equipment and the applicability of other industry standards that could provide better protection of equipment without incurring unnecessary costs.*

The majority of the industry standards for lightning protection are focused on safety and the protection of structures from lightning strikes. In addition, a large number of the standards emphasize the protection of power systems from the effects of lightning surges. Protection of ITS, traffic control and roadway lighting systems from lightning surges also involves the protection of low-voltage electronics and communications systems.

A study was conducted to identify the best practices nationally and internationally for the use of SPDs to protect electronics and related equipment similar to the ITS equipment used by the FDOT. Several different industries were examined to identify best practices in the use of SPDs to protect equipment of similar nature and exposure to lightning. However, it was found that there were very few industrial standard practices published. For example, the lightning protection of cellular towers was researched to identify common practices. However, the published sources found provided little detailed information on the use of the SPDs and the installation of lightning protection systems.

Given that there was little information on industrial best practices published the research focused on the best practices of state DOTs where lightning exposures were similar to Florida's, and to the recommendations of the Telecommunications Standards Sector of the International Telecommunication Union (ITU-T).

3.5.1 Best Practices of Other State DOTs

In Task 1, a survey was conducted of DOTs from states other than Florida to collect information on lightning protection measures used and what SPD studies had been conducted. The states surveyed included states where the largest number of lightning flashes were detected (from Vaisala's U.S. National Lightning Detection Network). The states included in the survey were (responses were received from the states in **bold**):

- **Alabama**
- Arkansas
- Georgia
- **Louisiana**
- **Mississippi**
- North Carolina
- **Tennessee**
- **Texas**

Contacts within each state were identified using the state's DOT website or through known contacts. Each state was contacted via email or telephone and asked the following survey questions:

1. What standards or methods are used in your state to protect roadside ITS, traffic control and lighting from surges due to lightning?
    a. Can I get drawings of standard installations including lightning protection?
    b. Do you have a standard set of surge protectors that you use or have approved for use?
2. Has your state conducted any studies on surge protection devices (SPDs) or surge protection techniques?
    a. Any laboratory of field test studies conducted?

The responses received from Alabama, Louisiana, Mississippi, Tennessee and Texas included some best practices for both the use of SPDs and other lightning protection techniques.

3.5.1.1 *Summary of the Other State DOT Best Practices in Lightning Protection and SPDs*

The material provided by each of the five responding states was reviewed to identify the current practices in lightning protection and SPD selection/installation use by each of the states. Note that most of the information provided related to examples of the methods and devices used and did not include overall standards or requirements. A summary of the current practices used by state is provided below:

Alabama

The Alabama DOT (ALDOT) provided several sections of the Alabama DOT Standard Specifications, 2012 Edition. The particular sections of interest (amended in 2013) were Section 730 Traffic Signals, Section 889 Roadway Lighting Materials and Section 890 Traffic Signal Equipment. Also included were excerpts for Intelligent Transportation Systems (ITS) installations.

The standards for lightning surge protection in the ALDOT Standard Specifications vary depending on the section of the standards. In some cases the standard includes the type of surge protection (e.g., metal-oxide varistors, inductive, …) or the number of stages for the surge arrestor. Some of the sections specify common specifications for SPDs including maximum current and clamping voltage while other sections only specify that a surge arrestor be present. The ITS standards include proper grounding of SPDs and that the ground rod or rods should provide a ground resistance of no more than 25 Ω.

Louisiana

The Louisiana DOT provided a summary from the 2006 Louisiana Standard Specifications for Roads and Bridges which summarizes the specifications for SPDs for ITS power, video and data surge protection. Also provided were drawings demonstrating SPD installation in CCTV cabinets and CCTV lowering devices.

The Louisiana DOT standards define the SPDs required for multiple ITS applications in standard SPD parameters including maximum surge current, clamping voltage and wiring requirements.

Each application includes an accepted Atlantic Scientific or Eaton SPD. No information was provided on ground rods or proper termination of the SPDs.

Mississippi

The Mississippi DOT provided drawings of roadway lighting lightning protection. In addition, an excerpt from the Mississippi Standard Specifications for Road and Bridge Construction (Section 907-649) on video Vehicle Detection was obtained.

The Mississippi DOT provided material provides very little information on the requirements or installation of the SPDs used in the roadway lighting or video vehicle detection installations. The standards for SPDs on the video vehicle detection installations defer to either NEMA standards or equipment manufacturer recommendations. The roadway lighting drawing provided do include ground rods and air terminals used on metal poles, and only indicate the use of a transient suppressor on the AC 480V power mains.

Tennessee

The Tennessee DOT indicated in their reply to the survey that they are "working on completing our standards and *Qualified Products List* for our ITS network." The DOT did provide excerpt from their Technical Special Provisions regarding surge protection for some of their projects. In addition, they provided some submittals from various projects that were essentially copies of data sheets from SPD manufacturers. The manufacturers' data sheets provided were from EDCO, Citel and Meter-Treater.

The excerpts provided by the Tennessee DOT covered specifications for Transient Voltage Surge Suppression (TVSS) on the load side of the main circuit breakers of the power supply, and surge protection for CCTV electrical interconnects.

While the Tennessee DOT requirements are currently not part of their permanent standards, these requirements do represent the best practice for SPD requirements in ITS installations.

Texas

The Texas DOT provided drawing for high mast roadway lightning poles, specifications for LED luminaires (including surge protection), and 2 documents on the assembly and materials specifications for solid-state traffic controller assemblies. The drawings and documents provided were reviewed to identify SPD specifications and other lightning protection measured defined in these documents.

The Texas DOT specifications provided specify SPDs for photocells on roadway lighting, luminaires, controller AC supply service, and a few miscellaneous low-voltage signals. The level of detail of the SPD specifications vary considerably with greater detail on SPDs for luminaires and AC power supplies. Also, there are specifications for air terminals and grounding for high mast roadway lighting poles.

3.5.1.2 *Summary of SPDs Standards and Best Practices in Similar States*

In this section, a summary of the SPD specifications provided by the states who responded to the survey will be presented. Some of the information provided by the states included other lightning protection measures used including ground rods and air terminals, however, the focus on this effort is the SPD standards and best practices. Based on the conclusion from Section 3.1 that the recommended testing of the performance of an SPD should be performed using the standard 1.2/50 µS - 8/20 µS Combination Wave, the parameters for these tests will be the focus of this summary.

Power Supply SPDs

Responses from 4 of the states (AL, LA, TN and TX) surveyed included specifications or recommendations concerning the selection and installation of SPDs to suppress lightning surges on power supplies for traffic control, roadway lighting and ITS systems.

AC Service Power

- Louisiana DOT specified that the SPD at the point of AC service from the utility (ITS installation) have the capacity to protect the system from a surge with a peak current of 200 kA per mode and 400 kA per phase.

Power Service Internal to an ITS, Roadway Lighting or Traffic Control System

- For AC power service and distribution within (load side of the breakers) a DOT roadside installation, most of the states surveyed recommended SPDs with a rating of between 13 kA and 20 kA. The only exceptions were that the Alabama DOT required a 50 kA SPD for AC power to roadway lighting, and Texas required a 70 kA SPD.
- Some DOTs included other specific requirements for SPDs including:
  - Alabama:
    - Traffic signal load switch SPDs: MOV-type, clamping voltage of 155 V.
    - AC service to Cabinet, and Controller Unit & Conflict Monitor SPDs capable of 25 surges of peak current 20 kA, clamping voltage 250 V maximum.
  - Louisiana:
    - CCTV AC service SPD with clamping voltage of 395 V maximum.
  - Tennessee:
    - AC Service Load Side Cab: response time up to 5 ns, 330 V max clamping per phase, 700 V line-to-line, and 70 kA peak current.
    - CCTV power SPD have a clamping voltage of 30 VAC(rms) or 42 VDC, a 3 kA peak current, and a response time up to 1 ns.
  - Texas:
    - Roadway lighting AC load side service SPD capable of 25 surges of peak current 20 kA.

Photocell and Luminaire SPDs

Alabama and Texas DOTs also provided some specifications for SPDs to protect photocells and luminaires on roadway lighting.

- Alabama:
  - Photocells: Required an "expulsion type surge arrester" meeting ANSI C136.10 with a peak current capability of 10 kA.
  - Luminaires:
    - Requires an SPD with a peak current of 45 kA (for 120 V AC service) and a 5 ns response time to a 700A/440V surge.
    - SPDs must be capable of enduring 40,000 surges at 700 A and 1,000 surges at 1 kA.
- Texas:
  - Photocells: Required an internal SPD on the photocells with a 2 kV sparkover and peak current of 5 kA.
  - Luminaires: Requires and SPD rated and tested (powered tests) to protect the luminaire for 5 surges at 10kV open-circuit and 10 kA short circuit.

Data and Video SPDs

The material provided by Louisiana, Tennessee and Texas DOTs included specifications for SPDs to protect data lines and video cables within ITS installations.

- Louisiana:
  - Video cable SPD: 10 kA peak current, rated voltage of 8 V (16 V peak-to-peak).
  - RS-422 serial data cable SPD: 10 kA peak current, 10 V clamping voltage.
  - RJ-45 Ethernet cable SPD: 1 kA peak current, 10 V clamping voltage.

- Tennessee:
  - Coaxial (video) cable SPD: 5 kA peak current, response time up to 1 ns.
  - Low-voltage signal (data) cable SPD: 10 kA peak current, capable of protecting for 25 surges with a peak current of 2 kA.

- Texas:
  - Twisted pair (data) communication line SPD: Peak voltage no more than 250V.

Sensor SPDs

Alabama and Texas DOTs also provided requirements for SPDs to protect from surges entering the cabinets through in-pavement loop sensors.

- Alabama: Loop SPDs protect up to 400 A, with a clamping voltage for a 250A surge of 25 V (35 V common mode) and a response time of 40 ns.

- Texas: Loop detectors require a surge suppressor.

3.5.2 Recommendations of the Telecommunications Standards Sector of the International Telecommunication Union (ITU-T)

The ITU-T recommendations are intended to apply to communications systems, including both wired and wireless communications. Some of the recommendations apply to scenarios or installations that are somewhat to very similar to FDOT ITS, traffic control, and roadway lighting installations. The ITU-T recommendations that were found to be most applicable or related to FDOT lightning protection needs include:

- ITU-T Rec. K.35 (05/96) Bonding Configurations and Earthing at Remote Electronic Sites
- ITU-T Rec. K.36 (05/96) Selection of Protective Devices
- ITU-T Rec. K.56 (01/2010) Protection of Radio Base Stations against Lighting Discharges
- ITU-T Rec. K.71 (06/2011) Protection of Consumer Antenna Installations

In addition to these standards, two summary papers largely relating to the ITU-T recommendations were used in this assessment:

- Barbosa, C., X. Ying, P. Day, and A. Zeddam, "Recent Progress of ITU-T Recommendations on Lightning Protection," 2011 7th Asia-Pacific International Conference on Lightning, November 1-4, 2011, Chengdu, China.
- Narayan, R., "Method for the Design of Lightning Protection, Noise Control and Grounding System at a Telecom Facility," INTELEC® 2014, 36th International Communications Energy Conference, September 28 – October 2, 2014, Vancouver, BC, Canada.

These recommendations and papers cover more than SPD selection and use. This section will focus on the recommendations for SPDs, and the remainder of the recommendations will be included in Task 3 of this project.

The ITU-T recommendations provide some general guidelines on the installation of SPDs, characteristics of some common SPD components, and some shielding recommendations to reduce induced surges on cables in or on external structures.

3.5.2.1 *ITU-T General Guidelines for Installing SPDs*

In the ITU-T recommendations the placement and grounding of SPDs is discussed for multiple scenarios. The recommendations include:

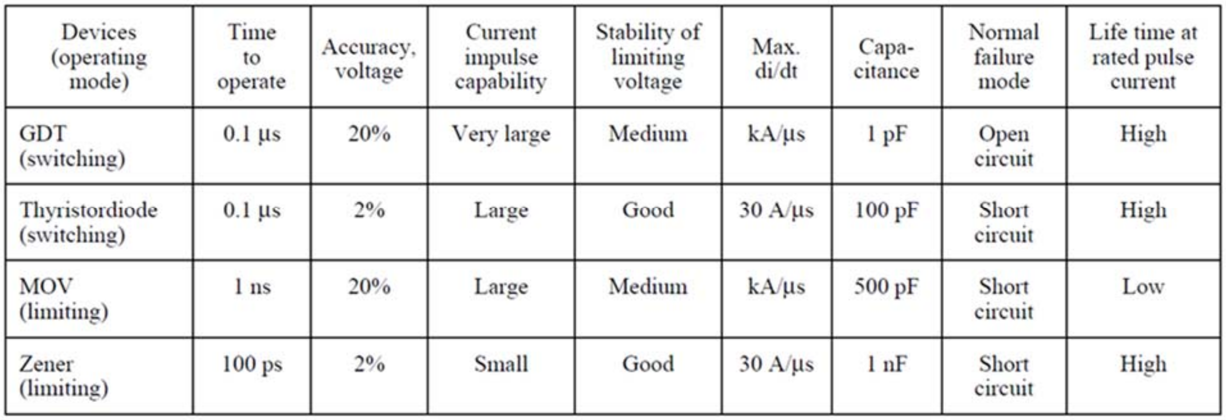
- SPDs should be placed where the conductors (wire, cables, etc.) enter the structure, cabinet, or housing containing electronic components. This indicates that if there are electronic components at both ends of a conductor, then SPDs should be installed at both ends.
- SPDs should be connected to protected conductors using the shortest wires feasible. Longer leads result in large inductive voltage drops increasing the risk of damage to both the SPD and the protected electronics.

- SPDs should be directly attached to the earth ground terminal (called the Main Earthing Terminal) using the shortest wires feasible. Typically, structures such as cabinets and DIN rails are not sufficient for proper grounding.
- SPDs should be connected to protect against both common mode and differential mode over-voltage conditions.
- SPDs should have a fast response time to limit the energy impacting the protected equipment during a surge.

These guidelines assume a proper earth grounding and bonding system is in place to dissipate the excessive surge currents to the earth and away from the protected systems.

3.5.2.2 *Characteristics of Common SPD Components*

ITU-T recommendation K.36 provides a table of general characteristics of "overvoltage protective components" (see Table 3.3). While recommendation K.36 is a relatively old recommendation (1995), these general characteristics are still instructive.



Devices (operating mode)	Time to operate	Accuracy, voltage	Current impulse capability	Stability of limiting voltage	Max. di/dt	Capa-citance	Normal failure mode	Life time at rated pulse current
GDT (switching)	0.1 µs	20%	Very large	Medium	kA/µs	1 pF	Open circuit	High
Thyristordiode (switching)	0.1 µs	2%	Large	Good	30 A/µs	100 pF	Short circuit	High
MOV (limiting)	1 ns	20%	Large	Medium	kA/µs	500 pF	Short circuit	Low
Zener (limiting)	100 ps	2%	Small	Good	30 A/µs	1 nF	Short circuit	High

Table 3.3. Characteristics of Common SPD Components (from ITU-T Rec. K.36)

Note in Figure 3.4 that there is a direct relationship between the current impulse capability and the time to operate (response time) of the SPD components. A typical modern SPD is a hybrid device typically using a combination of high capacity/slow speed components along with high speed/ lower capacity components to provide a higher level of protection. Also note that although the gas discharge tubes (GDT) are listed as having an open-circuit failure mode, there are GDTs designed to fail in a short circuit mode to prevent exposing sensitive electronics if the GDT fails.

Other guidelines for the selection of SPDs included in the ITU-T recommendations include:

- Characteristics of the SPD under normal (no surge) operation should have negligible effect on the power transmission, signaling, switching or other operation of the protected system. Examples include:
    - Bandwidth of the SPD should not impede performance of communication or video transmission.

  - Maximum operating voltage of the SPD should be chosen such that normal variation of the SPD characteristics due to environmental conditions and variations of the voltages on the protected wire or cable should not cause the SPD to become active.
  - For power systems protection, the SPDs should return to an off condition after a transient in order to prevent excessive heating and damage.
  - SPDs shall be selected to operate within specifications for the environmental conditions expected where the SPD is installed.
- Characteristics of the SPD under operating conditions (during transient or surge event):
  - SPD response time should be fast enough to prevent damage to protected components.
  - Large current capacity devices can be combined with more precise and faster secondary components to provide a fast response time and a well-defined clamping voltage (Note: typical in most modern SPDs that are commercially available).
  - SPDs should have the capability to survive and protect the equipment both at the expected maximum expected single surge, and against repetitive transients from lightning discharges.
  - Clamping voltages should be chosen to be above the peak operating voltage of the wire or cable to allow the SPD to recover (deactivate) after a transient passes. This is especially true for main power systems for safety reasons and to prevent damage to the SPD.
- Failure Modes of the SPDs:
  - SPDs should always be selected to fail in a "safe" condition. For examples:
    - SPDs protecting communication and video systems should fail as a short circuit. This will continue to protect the equipment, but also interrupt the operation of the system.
    - SPDs on AC power systems should fail as an open circuit. This will prevent the AC supply from shorting which could create excessive damage due to heat or fire. Fuses or circuit breakers can also be used to prevent this type of damage if the SPD fails as a short circuit.

3.5.2.3 *Shielding Recommendations to Reduce Induced Surges on Cables In or On External Structures*

While not directly related to the selection or installation of SPDs, ITU-T recommendation K.56 provides some guidelines to reduce induced lighting surges on cable or conductors in external areas such as towers. These guidelines appear to be applicable for FDOT installations that include roadway light poles, non-intrusive traffic sensors mounted on poles or elevated structures, variable message signs, or any other elevated structure containing electronic or electrical components.

ITU-T K.56 discusses the bonding and cabling for towers used in radio base stations. The recommendations include requirements for conducting lightning stroke current to ground and shielding of the waveguides, cables or wires from the effects of induced currents. There are other recommendations for earthing (grounding) and bonding of nearby structure, but these topics will be addressed in Task 3 of this project.

Metallic and Non-Metallic Towers

K.56 recommends that a metallic tower can be used to conduct the lightning stroke current to ground if the total cross-section of the tower structure is at least 125 mm^2. If the total cross-section of the metallic tower structure is less than 125 mm^2, then the tower shall be treated as a non-metallic tower.

For a non-metallic tower, K.56 recommends that tower have two (2) down-conductors to earth from the lightning rod. Each of the down-conductors shall have a minimum cross-section of 50 mm^2 and they shall *not* be insulated from the tower.

Bonding and Shielding of Cables and Wires in a Tower

The K.56 recommendation includes strategies for bonding of waveguides and coaxial feeder cables (for radio signals), and for power conductors (for tower lights). Waveguides are not used in ITS, traffic control and roadway lighting installations, however, the strategies for shielding and bonding of coaxial cables and power conductors can be applied to CCTV video cables, data wires/cables, and power conductors in FDOT poles and elevated structures.

Electromagnetic analysis indicates that a grounded metal shield around a conductor can effectively impeded inductive effects on the conductors within the shield. This is true even if the external conductor is carrying a current (e.g., from a lightning stroke). Therefore, the recommendations and strategies in K56 include the use of this type of shielding to reduce significantly induced currents of the cables in a tower (or other elevated structure).

Specifically, K.56 recommends that the outer conductor or shield of a coaxial cables should be electronically bonded to the down-conductor of the tower or the tower itself if it is a metallic tower. This bonding should occur at the top and bottom or the tower and at the entry point to any separate structure or cabinet. Note that power and other signal conductors can also be similarly shielded and thus installed and bonded in the same manner as a coaxial cable.

In addition, K.56 recommends that power conductors (this applies also to any conductors not inherently shielded like a coaxial cable) are to be installed within a metallic duct that is electronically continuous for its entire length. The recommended metallic duct is galvanized steel with a cross-section area of at least 16 mm^2, and the duct is to be electronically bonded to the metallic tower or down-conductor.

3.5.3 Conclusions and Recommendations on the Use of SPDs

The survey of DOTs in states that have similar lightning environments to that in the State of Florida demonstrated that the specifications and requirements for the use of SPDs and other lighting protection measures in these states are not complete for many applications. Where detailed specifications or requirements were provided, these requirements tended to be similar to the standards and best practices used within the Florida DOT. The specific ratings for the SPDs varied between the states, especially the peak surge current ratings. Some of the responding states had very specific specifications such as type of SPD or minimum response time for the SPD, while others indicated only the need for an SPD or that the SPD should meet the equipment manufacturers' specifications. Therefore, the responses to the survey provide only limited guidance in the selection and use of SPDs in Florida.

The recommendations from the ITU-T provide a more complete set of guidelines on lightning protection in general, and the selection and installation of SPDs. While most of these guidelines are already in use to some extent, the ITU-T SPD selection guidelines listed in Section 3.5.2.2 can be used to generate standards for SPD selection. Installing and grounding of SPDs per the ITU-T recommendations includes using separate conductors that are kept as short as practical for both connection to the protected conductors and the earth ground terminal.

The ITU-T recommendations also included guidelines for shielding and bonding conductors used in towers and elevated structures. The shielding and bonding methods in the recommendations can reduce the induced surge currents in these conductors and thus better protect the equipment both on the tower and in the cabinet from lightning-induced surge currents.

3.6 Conclusions and Recommendations for Task 2

Based on the research conducted in Effort 1 of Task 2, it is recommended that the standard combination waveform (1.2/50 μs voltage / 8/20 μs current) to evaluate and approve the performance of SPDs used in ITS installation in Florida shall be continued. The SPDs should be tested not only for verification of peak current capability, but also for the capability of the SPD to endure multiple surges.

The equipment necessary to create an SPD acceptance/performance test lab for the FDOT was identified, acquired and assembled. The primary equipment specified and acquired was (1) a MIG0606 Current Tester fitted with the TC-MIG24ED commercially available from EMC PARTNER AG, and (2) a Tektronix MDO3024 Mixed Domain Oscilloscope. Using this equipment the FDOT can test an SPD with up to a 6 kV open-circuit voltage / 6 kA short-circuit current. Test procedures are identified to perform acceptance and performance testing of SPDs.

A survey and assessment was conducted of the current maintenance and reporting procedures used to support ITS equipment in the various FDOT districts in Florida. It was determined that these maintenance and reporting procedures were generally being conducted by contractors and the methods, level of detail and data collected varied by district. It is recommended that a standard template for ITS maintenance reporting be defined and that all districts be required to include the template in contracts for ITS maintenance. This process will provide the FDOT the capability to monitor and evaluate lighting protection strategies and equipment across the state. The recommendations for data to be collected in the template and procedures to efficiently collect the data are provided in Section 3.4.

Finally, an assessment of best practices regarding the use of SPDs nationally was conducted. A survey was conducted of states other than Florida with high lightning exposure was conducted. Also, a literature survey was conducted to determine if best practices were defined in other applications that could be applied to SPDs for use in Florida ITS, roadway lighting and traffic control systems. The survey of state DOTs revealed that most of the states do not have a cohesive set of standards or requirements for SPDs. The few standards and requirements provided by the states were, for the most part, comparable to the standards or best practices currently in use in Florida. The literature search did not reveal any best practices in other industries that could be applied to Florida DOT applications. However, the research revealed that the Telecommunications Standards Sector of the International Telecommunication Union (ITU-T) has some published recommendations that provide guidelines for the selection and installation of SPDs in environments similar to those in FDOT roadside ITS, roadway lighting and traffic control installations. These guidelines, summarized in Section 3.5.2.2, can be used to generate standards for SPD selection.

4 Summary of Task 3: Review of the Effectiveness of Lightning Termination Devices

Task 3 consisted of two efforts:

- Effort 1: Assess Current Research and Best Practice Concerning Lightning Termination Devices.
- Effort 2: Field Tests With and Without Air Terminals.

The following sections (Section 4.1 & 4.2) correspond to the two (2) deliverables delineated in the *Exhibit A – Scope of Service* for this project. The deliverables are as follows:

1. Review of NFPA 780, and Current Research and Best Practice Concerning Lightning Termination Devices (Section 4.1)
   A report that identifies the applicability of best practices outlined in NFPA 780 and current practice/research as related to the use of air terminals at FDOT traffic control (including ITS) and lighting field sites.

2. Assessment of Effectiveness and Necessity of Air Terminals (Section 4.2)
   A report that identifies the effectiveness and necessity of air terminals used at ITS, traffic control and roadway lighting installations.

4.1 Review of NFPA 780; Current Research and Best Practice Concerning Lightning Termination Devices

> *A report that identifies the applicability of best practices outlined in NFPA 780 as related to the use of air terminals at FDOT traffic control (including ITS) and lighting field sites.*

Lightning termination (i.e., air terminals, lightning rods, etc.) is a topic that has been widely discussed and researched over the past several decades. The NFPA 780 Standard for the Installation of Lightning Protection Systems addresses the use of air terminals for lightning strike termination, the techniques required to conduct the lighting current to ground, the design of grounding electrodes to dissipate the current into the earth, and surge protection devices intended to protect electrical and electronic devices. The primary purposes or goals of the NFPA 780 standards is the protection of life and property (in particular, structures) in the event of lightning strikes. While there is some applicability to the FDOT needs to protect ITS, roadway lighting and traffic control equipment, the NFPA 780 standard was not intended to be guide for the protection of roadside equipment.

A set of standards (recommendations) for lightning protection have been identified that more closely relate to the needs for lightning protection of roadside equipment. These recommendations are from the Telecommunications Standards Sector of the International Telecommunication Union (ITU-T). The ITU-T recommendations are intended to apply to communications systems including both wired and wireless communications. One of the recommendations, K.56 Protection of Radio Base Stations Against Lightning Discharges, applies to scenarios or installations that are somewhat to very similar to FDOT ITS, traffic control and roadway lighting installations.

The current state of practice of lightning protection can be summarized in 4 parts (adapted from *Fundamentals of Lightning Protection Systems*, a professional development course by John Tobias, Continuing Education and Development, Inc.):

1. Lightning Strike Termination
2. Conductor to Ground
3. Grounding Electrodes to Disperse Current into the Earth
4. Surge Protection Devices

This section will address the topics: 1) lightning strike termination, 2) conductor to ground and 3) grounding electrodes. Surge protection devices were covered in Task 2 of this project. The emphasis of this section will be on the lighting strike termination, but conducting the current to ground and grounding electrodes will be addressed for completeness. First, the NFPA 780 standard will be reviewed as it applies to these topics. Then the ITU-T recommendations will be reviewed and summarized as they pertain to FDOT roadside equipment protection.

4.1.1 Review of NFPA 780

The National Fire Protection Association (NFPA) publishes code #780 titled "Standard for the Installation of Lightning Protection Systems (LPS)", is considered to be the national design guide for complete lightning protection systems in the United States. The most recent edition of this code will be released in 2017. The changes in the 2017 version of the code are not significant to FDOT installations, therefore the 2014 version of NFPA 780 is used for this review.

According to LPS defined in NFPA 780, there are five elements that need to be in place to provide an effective lightning protection system; 1) strike termination devices, 2) conductors, 3) grounding electrode system, 4) bonding of the termination systems, conductors and electrodes, and 5) Surge Protection Devices (SPD). When these elements are identified properly in the design stage, incorporated into a neat workmanlike installation, and no changes to the building occur, the system will provide protection against lightning damage.

The recommendations and suggestions for the protection of roadside equipment based on the applicable standards in NFPA 780 are presented in the following sections.

4.1.1.1 *Strike Termination Devices*

A strike termination device is to intercept the direct lightning attachment of a lightning flash and connects it to a path to ground. A strike termination device may include air terminals, metal masts, overhead wires, or permanent metal parts of a building. Any metallic body of a structure that is exposed to direct lightning flashes, and that is 3/16" thick or more may serve as strike termination device. Therefore, in some cases construction elements such as the metal poles used to mount ITS devices may be utilized as strike terminations.

Air Terminals

Air terminals (lightning rods) are the primary lightning strike termination devices used for lightning protection. NFPA 780 provides the following requirements for the design and installation of air terminals.

The tip of an air terminal shall be not less than 10" above the object or area to be protected. Air terminals exceeding 24" in height shall be supported at a point not less than one-half their height. For structures not exceeding 75 feet in height, NFPA has the following minimum material requirements for the air terminals:

- For air terminals made of copper:
  - Minimum diameter of a solid air terminal is 3/8" (9.5 mm).
  - Tubular air terminals have minimum diameter of 5/8" (15.9 mm) and a minimum wall thickness of 0.033" (0.8 mm).
- For aluminum air terminals:
  - Minimum diameter of a solid air terminal is 1/2" (12.7 mm).
  - Tubular air terminals have a minimum diameter of 5/8" (15.9 mm) and a minimum wall thickness of 0.064" (1.63 mm).

The tips of the air terminals can be sharp or blunt.

Lightning Protection Masts and Overhead Ground Wires

NFPA 780 also allows separate structures such as grounded masts or overhead ground wires for use as lightning termination devices. These devices are typically installed near or over the structures to be protected. Installing these separate structures would be costly for ITS and roadway lighting installations and thus have little applicability to the FDOT.

Strike termination devices for different types of roofs are also discussed in NFPA-780, but again due to its irrelevance to ITS roadside equipment installations they are not mentioned in this report.

Zone of Protection

The number, size and placement of air terminals is determined by evaluating the physical characteristics if the structure or structures to be protected. The area near to lightning protection system (i.e., one or more properly grounded air terminals) that is considered protected from a direct lightning strike is defined as zone of protection. NFPA 780 prescribes three methods to calculate the zone of protection depending on the size and geometry of the structure to be protected: 1) air terminal placements, 2) the angular method, and 3) the rolling sphere method.

Air Terminal Placement Method - NFPA 780 discusses the placement of air terminals for different types of roofs, including flat roofs and various types of pitched roofs. For example, for flat roofs the standard requires air terminals at intervals not to exceed 20 – 25 feet (depending on air terminal height) around the perimeter of the building. If the roof is wider that 50 ft. in length or width, then additional air terminals are required such that the air terminals have a maximum spacing (A) of 50 ft. Since most FDOT roadside installations do not resemble the geometry of roofed structures, this method has very limited applicability to FDOT installations of ITS, traffic control or roadway lighting installations. The angular method and the rolling sphere methods are more applicable and thus are discussed in the following sections.

Angular Method - The angular method is considered to be the older method to determine the placement of strike termination devices. It is based on similar technical grounds as the rolling sphere method and can be used as a simplified (and conservative) method to determine the zone of protection for structures up to 50 ft. in height. For structures having height less than 25 ft, a 60 degree or 1:2 angle method is used as shown in Figure 4.1 to identify the zone of protection from direct lightning strikes. Whereas, for structures between 25 ft. and 50 ft., a 45 degree or 1:1 angle method is used to determine the placement of strike termination devices as shown in Figure 4.2. The zone of protection for the angular method is the area below the sloped lines from the higher air terminal shown in Figures 4.1 and 4.2.

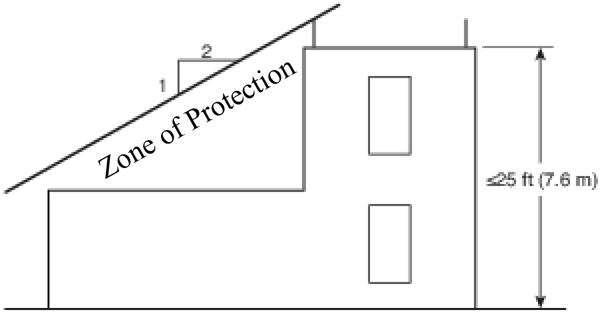


Figure 4.1. Lower Roof Protection for Flat-Roof Buildings 25 ft or Less in Height

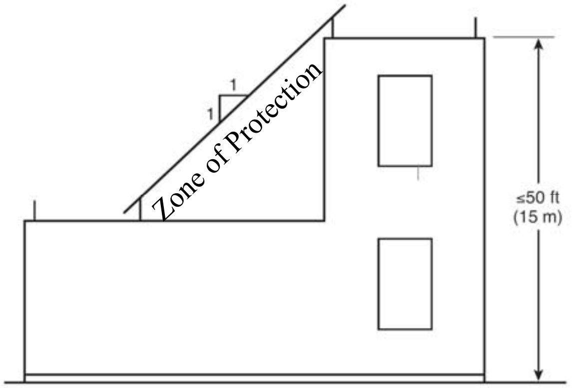


Figure 4.2. Lower Roof Protection for Flat-Roof Buildings 50 ft or Less in Height

Rolling Sphere Method - The Rolling Sphere Method (RSM) is the third (and perhaps the most useful for FDOT roadside structures) method in NFPA-780 to determine strike termination devices and zone of protection for lightning protection system. The RSM is based on an electrogeometric model (EGM) used to model attachment of a lightning strike (striking distance) to a grounded object. The striking distance (in meters) is $d_s = 10I_p^{0.65}$, where I_p is the peak current of the strike (kA). Since strike currents of 10 kA or more represent over 90% of the lightning events, I_p is set to 10 kA, resulting in a strike distance of approximately 150 feet (~45 m). Note that in Chapters

7 and 8 of the NFPA, a smaller strike distance of 100 feet (~30 m) is used in determining the area of protection for flammable or explosive material. This striking distance corresponds to a peak lightning current of about 5 kA, and is used to increase the level of lighting protection for dangerous material.

The RSM is a simplified or visual implementation of the EGM. An imaginary sphere of radius $R = d_s$ (typically, R is 150 ft. or 100 ft.) is rolled over the structure such that the sphere is tangent to the earth and resting on all the termination devices (see Figure 4.3). All the area under the rolling sphere between points of contact with the earth is the zone of protection provided by the structure and the lightning protection system. Using the RSM, a designer can select the number and locations of air terminals or other lightning terminations to provide the desired zone of protection.

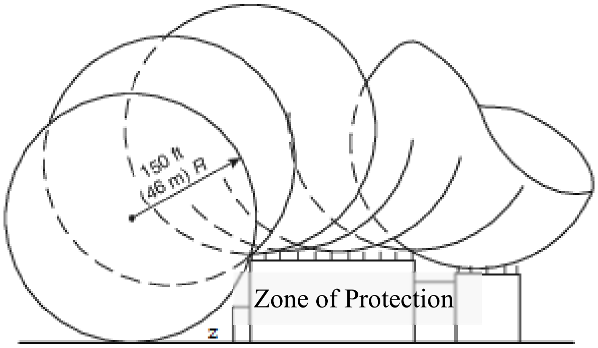


Figure 4.3. Zone of Protection Using Rolling Sphere Method

Note that the zone of protection determined using the angular method (for structures up to 50 ft.) is a conservative estimate of the zone of protection determined using the RSM. Any object within the zone of protection determined by the angular method will also be within the zone of protection determined using the RSM. Therefore, the angular method can be used for FDOT roadside installations with heights up to 50 ft.

4.1.1.2 *Conductors*

The NFPA 780 standard also provides useful guidance for the implementation of conductors to provide a low impedance path from the strike termination device to the grounding electrodes or earth. The standard defines material and size requirements for two classes of conductors: (1) main conductors (for connecting strike termination devices to other strike termination devices or to grounding electrodes) and (2) bonding conductors (used for equalizing potentials between the lightning protection system and nearby conductive object). Only main conductors are designed to transport the majority of the lightning current. Bonding conductors equalize potential for grounded metal structures, nearby metallic structures, and similar uses such as bonding the utility power ground to the lightning protection system.

For structures up to 75 ft. height, a copper main conductor cable must have a minimum cross-section area of 0.0451 in^2 (29 mm^2). In terms of the American wire gauge, the main conductors must be #2 AWG (0.0521 in^2 or 33.6 mm^2) or lower. If a stranded wire is used, then the size of each strand must have be #17 AWG or lower. For main conductors made of aluminum, the gauge of the wire must be #1/0 or lower and strands must be #14 AWG or lower. The main conductor can also be a solid copper or aluminum strip. If the strip is copper, it must have a minimum thickness of 0.051 in and minimum cross-section area of 0.0451 in^2 (29 mm^2). If the strip is aluminum, it must have a minimum thickness of 0.064 in and a minimum cross-section area of 0.0775 in^2 (50 mm^2).

If bonding conductors are used, they must conform to the following requirements. The bonding cables must be #6 AWG or lower if copper and #4 AWG or lower if aluminum. Bonding strips must have a minimum width of ½ in and a minimum thickness of 0.051 in (copper) or 0.064 in (aluminum).

The NFPA 780 standard provides following requirements for main conductors between air termination devices, and between air termination devices and grounding electrodes:

1. For most cases, the main conductors shall provide 2 or more paths from each strike termination device to the grounding electrodes.
2. The main conductor paths to the grounding electrodes shall be horizontal, downward (slight rising paths allowed up to a ¼ slope).
3. The down conductors shall contain no bends greater than 90 degree or bends with a radius less than 8 in.
4. The metal framework of the structure can be a substitute for a main conductor if the structure is electrically continuous and at least 0.1875 in (4.8 mm) in thickness.
5. If the down conductor is on or in a reinforced concrete column, the down conductor shall be connected (bonded) to the reinforcing or structure steel in the column at both the top and bottom of the column.
6. Connectors used in the lightning protection system shall be secured by bolting, brazing, welding, screwing or high-compression connectors, and shall be attached in such a way to withstand a 200 lb. (890 N) pull test.

The NFPA 780 requirements for the grounding conductors are mostly applicable to the FDOT roadside equipment installations. Even providing 2 ground paths will reduce the electrical impedance of a lightning strike current (significantly more than using a larger down conductor).

4.1.1.3 *Grounding Electrode System*

The NFPA 780 standard prescribes the requirements and standards for multiple types of grounding electrodes including ground rods, ground rings, radial electrodes, plate electrodes and concrete-encased electrodes. The primary types of interest and use by the FDOT are the ground rods and possibly the concrete-encased electrodes. The other types of grounding electrodes are typically used in shallow topsoil or rocky terrain not common in Florida. The standard also provides for the use of multiple grounding electrodes for high resistivity soils such as sand or gravel.

Note that all grounding electrodes shall be bonded together at a single point no more than 12 ft. in elevation. This provides a common ground location which shall be bonded to grounded metal enclosures, and the ground references for the electric power system, antennas, communication systems, etc. within the structure.

Ground Rods

The length of ground rods shall not be less than 8 ft. (2.4 m) in length, and have a minimum diameter of 1/2" (12.7 mm). The ground rods shall extend vertically not less than 10 ft. (3 m) into the earth. The earth shall be compacted and made tight against the length of the conductor and ground rod, as shown in Figure 4.4. Rods should not be covered with any insulating material.

Multiple ground rods may be used to achieve the desired ground resistance especially in sandy soil conditions. When using multiple ground rods, the separation between any two ground rods shall be at least the sum of their driven depths, where practical. The standard also recommends that multiple ground rods be connected by ground loop conductors with the same requirements as the main grounding conductors. This recommendation is a requirement if the structure is over 60 ft. in height.

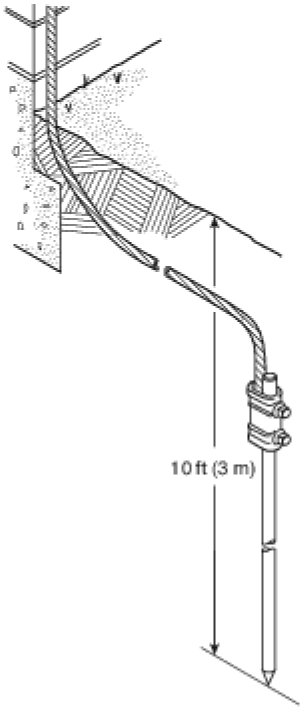


Figure 4.4. Single Ground Rod Installation

Concrete-Encased Grounding Electrodes

The NFPA 780 standard allows for the use of concrete-encased electrodes for grounding only in new constructions. The concrete-encased electrodes must meet the following requirements:

1. The electrode shall be located near the bottom of the concrete foundation and in direct contact with the earth.
2. The electrode shall be encased by not less than 2 in (50 mm) of concrete.

3. The encased electrode shall consist of one of the following:
    a. At least 20 ft. (6 m) of bare copper wire meeting the requirements of a main conductor, or
    b. At least 20 ft. (6 m) of one or more steel reinforcing bars that are bonded together and each having a diameter of at least ½ in.

4.1.1.4 *Surge Protection Devices*

To protect electrical system hardware like CATV, alarm, lights, antenna systems, etc. surge protection devices are permanently installed. SPDs shall be installed at all power service entrance. The SPD shall protect against surges produced by a 1.2/50 µs and 8/20 µs combination waveform generator. SPDs at the service entrance shall have a nominal discharge current (I_n) rating of at least 20kA 8/20 µs per phase. SPDs shall be used to protect signal, data and communication system, and for this purpose SPDs shall have a maximum discharge current (I_{max}) rating of at least 10kA 8/20 µs when installed at the entrance. SPDs shall not be grounded through a down conductor of the lightning protection system (i.e., down conductor from an air terminal). SPDs protecting communications systems shall be directly grounded to the common ground.

4.1.2 ITU-T Standards

NFPA 780 standard gives recommendations for the protection of buildings and equipment against fire damages due to lightning strikes. Some of the requirements in this standard can be applied to the protection of FDOT roadside equipment including ITS, traffic control and roadway lighting. Another recommendation (voluntary standard) has been identified that may also be applicable to the lightning protection of FDOT roadside equipment. The ITU-T K.56 "Protection of radio base stations against lightning discharges" specifically deals with the protection of telecommunication towers and base station against lightning. The geometry, infrastructure, and design of a telecommunication tower and Radio Base Station (RBS) resembles that used in some FDOT roadside equipment such as CCTV or MVDS poles, roadway lightning, or DMS structures.

The International Telecommunication Union (ITU) is an organization of the United Nations (UN) committed to the development of telecommunications worldwide. ITU-T is a branch of ITU, which is devoted to the standardization activities on telecommunications. In this section, the ITU-T K.56 is assessed with respect to its applicability to FDOT roadside equipment installation. The ITU-T K.56 presents recommended protection techniques applied to a telecommunication RBS and telecommunication tower in order to protect them against lightning flashes. The lightning protection system defined in ITU-T K.56 contains four elements:

1. Lightning Protection System or LPS (includes lightning termination and conducting the lightning current to ground),
2. Bonding,
3. Earthing (i.e., grounding and ground rods), and
4. SPDs.

The general view of telecommunication tower and the radio base station presented in the ITU-T K.56 recommendation is shown in Figure 4.5. The sections referred to in this figure are the specific sections of ITU-T K.56. This structure is similar in structure to a CCTV or MVDS pole, DMS structure, or roadway lighting pole connected to a detached (or even attached) equipment cabinet. The recommendations in the ITU-T K.56 will be summarized below with respect to its applicability to the FDOT roadside installation lightning protection. Comparisons between the ITU-T K.56 recommendations and related requirements in the NFPA 780 standard will be included.

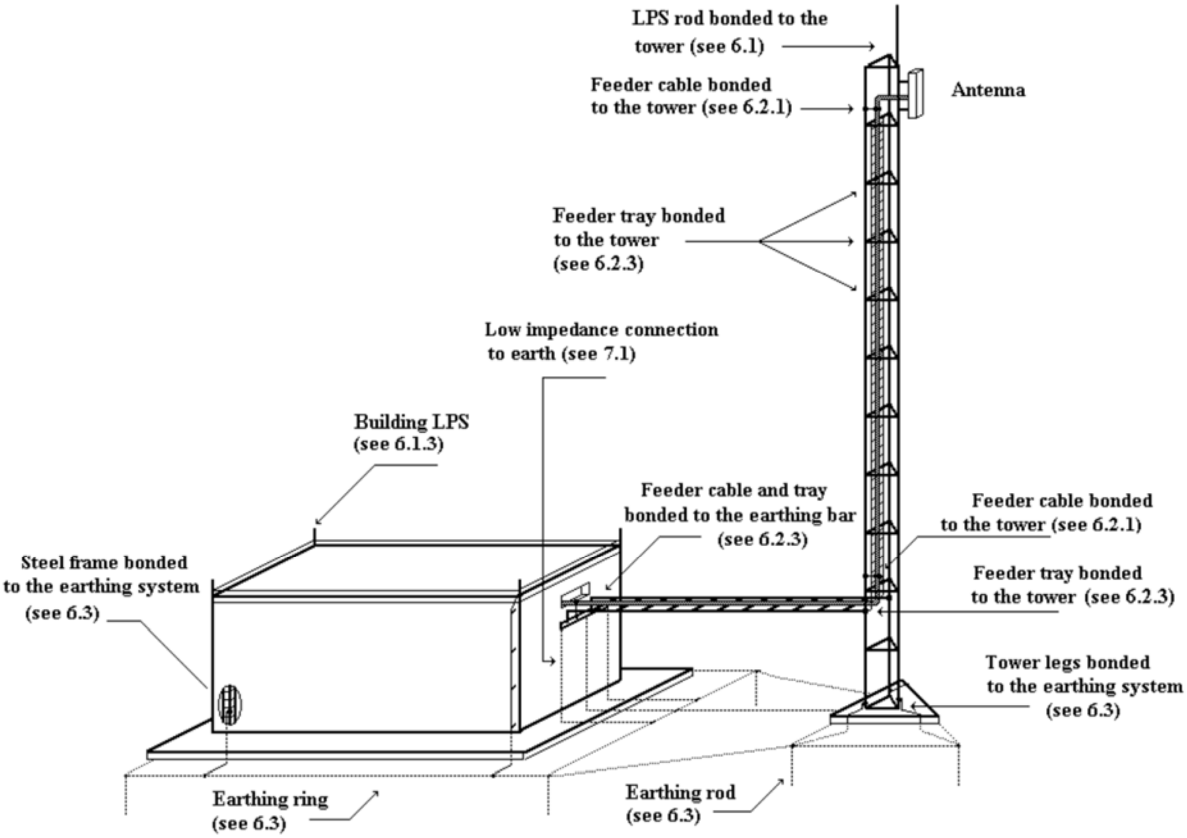


Figure 4.5. View of External Lightning Protection for a RBS and Telecommunication Tower

4.1.2.1 *Lightning Protection System (LPS)*

The ITU-T K.56 recommendation indicates that lightning rods (air terminals) may be needed to protect the equipment on the tower from a direct lightning strike. The size, location and number of rods, and even the need for a lightning rod can be assessed using the rolling sphere method (RSM). The K.56 does not indicate whether or not the metal structure of the tower can be used for lightning termination. The rolling sphere method can also be used to determine if the building (or roadside cabinet) is protected by the lightning rod(s) or whether the building requires a separate LPS. For most FDOT roadside equipment installations the air termination on the poles or structures will provide protection for the nearby cabinets.

The conducting of the lightning current from the tower to the earthing system depends on the tower's structure.

Metallic Structure

If the structure of the tower (or pole) is of metal with a cross-section area of at least 125 mm^2 that is electrically continuous, then a lightning rod can be connected to a tower. The metallic structure of the tower will conduct the lightning strike current to ground and there is no need of separate down conductors.

Non-Metallic Structure

If the structure of the tower (or pole) is not metallic (e.g., wood or concrete), or if the metallic structure has a cross-section less than 125 mm^2, or if metallic structure is not continuous, then separate down conductors must be added to conduct the lightning current to ground. The ITU-T K.56 recommends that two down conductors be installed to connect the lightning rod(s) to ground. The down conductors shall not be insulated from the tower and they shall have a minimum cross-section of 50 mm^2 each (NFPA 780 requires two copper conductors each with cross-section areas of at least 29 mm^2 for structures up to 75 ft., and 58 mm^2 for taller structures). The down conductors shall be installed on opposite side of the poles.

4.1.2.2 *Bonding*

Bonding in the context of the ITU-T K.56 recommendation focuses primarily on the concept of bonding the shielding or metal conduit for signal and power conductors to the lightning protection system. This type of bonding is not included in the NFPA 780 standard, but may be helpful in reducing the damage caused by lightning surges. The ITU-T K.56 recommends that all power and signal cables be shielded by either a continuous metallic duct or by using shielded cables.

Metallic Duct

An unshielded cable should be installed inside a metallic duct and this duct shall be electrically continuous for its entire length. The duct shall be bonded to the metallic structure (pole) or down conductor at least at its upper end and also bonded to the earthing (grounding) system at the entrance to the structure or cabinet. The length of the cable that may run outside the metallic duct shall be as short as possible. The metallic duct can be made of galvanized steel and shall have a cross section are not less than 16 mm^2.

Shielded Cable

A shielded cable can be installed directly along the metallic structure (pole) or down conductor (without a metallic duct). The shield of the cable shall be electrically continuous for its entire length and shall be bonded to metallic structure (pole) or down conductor at its upper end. It also shall be bonded to the earthing or grounding system at the entrance to the structure or cabinet.

Unshielded Cable

The use of unshielded power cable installed without a metallic duct requires the installation of adequate SPDs close to the electronic equipment on the tower and connected between the conductors and the metallic structure or down conductors. Another set of SPDs is also required at the point of entrance to the structure or cabinet. These SPDs should be earthed properly.

Note that unlike typical FDOT roadside systems, the only power required on most radio base station tower is for lighting. Most of the electronic equipment is located within the RBS structure. Shielding of the power and signal cables on FDOT roadside installations can help reduce the likelihood of flashover from direct lightning strikes to the cables. In addition, the shielded cables will be much less susceptible to inductive coupling from nearby lightning strikes. However, it is advisable that SPDs be installed for all power and signal cables at the top of the tower and in the cabinets.

4.1.2.3 *Earthing*

The earthing or grounding system is intended to provide a safe path for the lightning current to earth and to reduce the potential difference at the earth surface around a facility or structure. The task here is to keep earthing resistance (impedance) as low as possible. The main characteristics of this earthing system described in ITU-T K.56 are listed below:

- A bare conductor shall form a ring electrode around every structure needed to be protected. In case of more than one rings, multiple earthing conductors are used to interconnect them.
- The distance of the buried conductor from the associated structure shall be approximately 1m, and the depth of the conductor shall be at least 0.5 m.
- Vertical rods should be installed along the ring electrode. These rods should be made of steel covered with copper or made of galvanized steel, and they shall be attached to the earth electrode by appropriate connectors.
- The legs of metallic structure (or the down conductors of a non-metallic structure) shall be bonded through short connections to the structure's earthing ring. The steel reinforcement of the tower's basement, if any, shall also be connected to the earthing ring.
- If the structure is metallic, its feet shall be bonded to the earthing ring.
- The earthing conductor shall be as short as possible and have 50 mm^2 as the minimum cross-section area.
- All conductors in contact with the earth should be made of copper or steel covered with copper and have 50 mm^2 as the minimum cross-section area. Galvanized steel conductors can also be used, with 90 mm^2 as the minimum cross-section area.

- The bonding should be made by a copper conductor and connected to the nearest earth electrode. Alternatively, a steel conductor covered with copper or galvanized steel conductors could also be used.

- The length of the ground conductors to the earthing rods and bonding rings shall be as short as possible.

The earthing or grounding recommendations in the ITU-T K.56 differ from the requirements in the NFPA 780 in a few key aspects. The most significant difference is that the K.56 recommendation calls for a ring electrode around each structure (tower, buildings, etc.), and that the separate rings should be bonded together by two or more bonding conductors. This is the concept of providing an equipotential plane around all the interconnected structures. The NFPA 780 requirements do not call for ring electrodes in cases where the height is less than 75 ft. Also, the NFPA 780 does not call for bonding of earthing systems for nearby structures.

4.1.2.4 *Surge Protection Devices*

Like the NFPA 780, the ITU-T K.56 recommendation calls for a single common grounding point (referred to as the main earthing bar or MEB) to which all SPDs are connected in the building (RBS) or cabinet. At the top of the tower, the SPDs are attached to the LPS (air terminal or down conductor).

The ITU-T K.56 recommendation calls for SPDs with maximum ratings defined using either the 8/20 or 10/350 impulse current shape. It primarily provides guidance on the size and configuration of the SPDs to be attached to the user side of the power service. Typical maximum peak surge ratings recommended for these SPDs are 40 – 60 kA. Leads on the SPDs are to be kept as short as possible to reduce the inductance and resistance of the wiring. The configuration or scheme for installing the SPDs on the 3-phase power systems are recommended for each type of electrical power system used. The power system types (TN-C, TN-S, TT, IT, etc.) differ according to whether or not the neutral wire is connected to earth ground and the existence of a separate protective earth (PE) wire is included.

The ITU-T K.56 also recommends SPDs in the building (RBS) for the lighting power cables and the coaxial cables to the antennas. It also recommends SPDs with peak surge ratings of 20 – 40 kA on the tower for the lighting power cables if unshielded cables are used to supply the power. Specific rating for these SPDs for the coaxial (signal) cables are not provided in the recommendation.

4.1.3 Conclusions and Recommendations from NFPA 780 and ITU-T

Based on the assessment of the NFPA 780 and ITU-T K.56 standards, the following recommendations and conclusions are presented. While the central focus of this effort was on the air terminals, the recommendations below include recommendations for the conductors and ground rods as well.

1. The use of air terminals (lightning rods or the metal structure) is included in both standards. However, air termination only provides protection from a direct lightning strike. However, it may not be economically advantageous to add air terminals to installations with lower risk of direct lightning strike (e.g., shorter poles or pole protected by taller nearby structures) or which are less costly to replace if severely damaged.
2. If the pole is a metallic structure that is at least 3/16" thick, then the pole can be used as a strike termination device and thus the addition of an air terminal may not be needed. However, the slope or rolling sphere methods should be used to ensure that the equipment on the poles are protected from direct lightning strikes. Additional air terminals can be installed to provide the protection for the equipment installed on the poles.
3. If the structure is of metal, continuous to ground, and has a cross sectional area more than 125 mm^{2,} it can be used as down conductor, otherwise, a minimum of two separate down conductors each having cross sectional area of at least 29 mm^2 (copper) or 50 mm^2 (aluminum) must be used. The ITU-T recommendation calls for larger cross-section area conductors, but it is more advantageous to have multiple conductors than to have larger conductors.
4. Reinforced concrete poles with air terminals require down conductors. The reinforcing steel of the pole can be used as the down conductor provided the reinforcing rods have a total cross-section area or at least 125 mm^2. Otherwise, at least two down conductors each with a cross-section area of 29 mm^2 (copper) or 50 mm^2 (aluminum) must be used.
5. The unshielded cables that are used for providing electric power and signaling to the electronic equipment on structure to be protected, should be enclosed, where practical, inside a metallic duct. The metallic duct to provide protection to cables must be continuous, bonded at the top to the down conductors, bonded at the cabinets to earth ground and have cross-section area not less than 16 mm^2. Shielded cables can be used without metallic duct provided the shields are bonded as described for the metallic ducts. The lengths of unshielded cables (e.g., past the end of the metallic conduit) on the tower should be kept to a minimum to reduce induced currents on the cables.
6. The length of ground rods shall not be less than 8 ft. (2.4 m) in length, and have a minimum diameter of ½" (12.7 mm). The ground rods shall extend vertically not less than 10 ft. (3 m) into the earth. Ground rods should be installed as close to the structure being protected and with as short a ground wire as practical.
7. If multiple ground rods are required to achieve the desired maximum ground resistance, the separation between any two ground rods shall be at least the sum of their driven depths, where practical.

4.2 Assessment of Effectiveness and Necessity of Air Terminals

> *A report that identifies the effectiveness and necessity of air terminals used at ITS, traffic control and roadway lighting installations.*

The original intent of Effort 2 in Task 3 was to identify a location within a lighting-prone region of Florida where a field test could be conducted to test the effectiveness of air terminals regarding the protection of ITS, roadway lightning and traffic control equipment. Several locations were considered for these tests but no location was identified that contained a good mix of roadside equipment and was free from tall structures and power lines that could bias or significantly alter the results of the tests. This section will summarize the efforts to identify a test site and identify the strengths and weaknesses of each site. No suitable test site was identified to conduct the air terminal field test. Instead, a forensic assessment of maintenance data was used to provide some assessment of the effectiveness and necessity of air terminals.

4.2.1 Potential Field Test Sites Considered

Working with the FDOT, attempts were made to find a location with a significant number of closely located roadside equipment installations in an area of high lightning density. The intent was to install or remove air terminals (and grounding cables) as necessary to produce alternating sites that are protected by air terminals and left unprotected. To provide a statistically significant data set, the test site would need to be monitored over multiple months, particularly summer months. From previous tests performed by this research team, a particularly good location for such a test will be in the area around District 7.

Potential test sites were identified using input from the FDOT, searches for DMS locations using the Florida 511 website, and online investigations of interstate and arterial locations using Google Maps (Street View) and Google Earth. Three potential test sites were identified for consideration as the field test site for this effort:

1. US 301 in Hillsborough County between Balm Road and Gibsonton Drive,
2. I-275 is Saint Petersburg between I-375 and Roosevelt Boulevard, and
3. I-4 near Tampa.

Each of the potential air terminal field test sites were evaluated and found to have shortcomings such as overhead power lines, limited variation in air terminal installations and heavy traffic volume. They were determined to not be suitable for conducting a field test to assess the effectiveness of air terminals in protection ITS, roadway lightning and traffic control equipment.

4.2.2 Forensic Analysis of Maintenance Data to Assess the Effectiveness and Necessity of Air Terminals

In order to identify the effectiveness and necessity of air terminals used at ITS, traffic control and roadway lighting installations, it was decided to forensically assess maintenance records for existing installations. For this approach one or more sites needed to be identified where there are similar installations with and without air terminals installed for which there are multiple years of maintenance records available. While an ideal site where installations alternate between having and not having air terminals installed is unlikely, this approach would include the data from a longer period of time, making the results more statistically significant.

4.2.2.1 *MVDS Installations with Concrete Poles on I-4*

The review of the ITS installations along I-4 revealed that there were a significant number of MVDS installations where some had air terminals installed and others did not. Reviewing these sites using Google Earth revealed that most of these MVDS installations were mounted on approximately 20-foot-tall reinforced concrete poles. Therefore, this site was used for forensic analysis of the possible and likely lightning-caused damage to determine the effectiveness and necessity of air terminals for MVDS installations using 20-ft. reinforced concrete poles.

I-4 Site Description

According to the records provided by FDOT District 7, the MVDS installations on I-4 from mile marker (MM) 3.5 to about MM 22.4 (Hillsborough County) were installed without air terminals on the concrete poles. The MVDS installations on concrete poles from MM 22.4 to MM 54.1 (Polk County) were installed with air terminals installed. Figure 4.6 shows the lightning flash density (average flashes/km^2/year for 2005-2014) and highway map for west central Florida, including Hillsborough and Polk counties. In Figure 4.6, it can be seen that I-4 in Polk and Hillsborough counties is within a high lightning density area. However, the lightning density in Polk County is 10 – 20% lower than in Hillsborough County. Therefore, within this test site, the area where the MVDS poles have air terminals (MM 22.4-54.1, Polk County), there will be 10–20% less likelihood of lightning strikes than in the area where the MVDS poles do not have air terminals (MM 3.5-22.4, Hillsborough County). This will have to be taken into account in the final assessment of the forensic maintenance comparison.

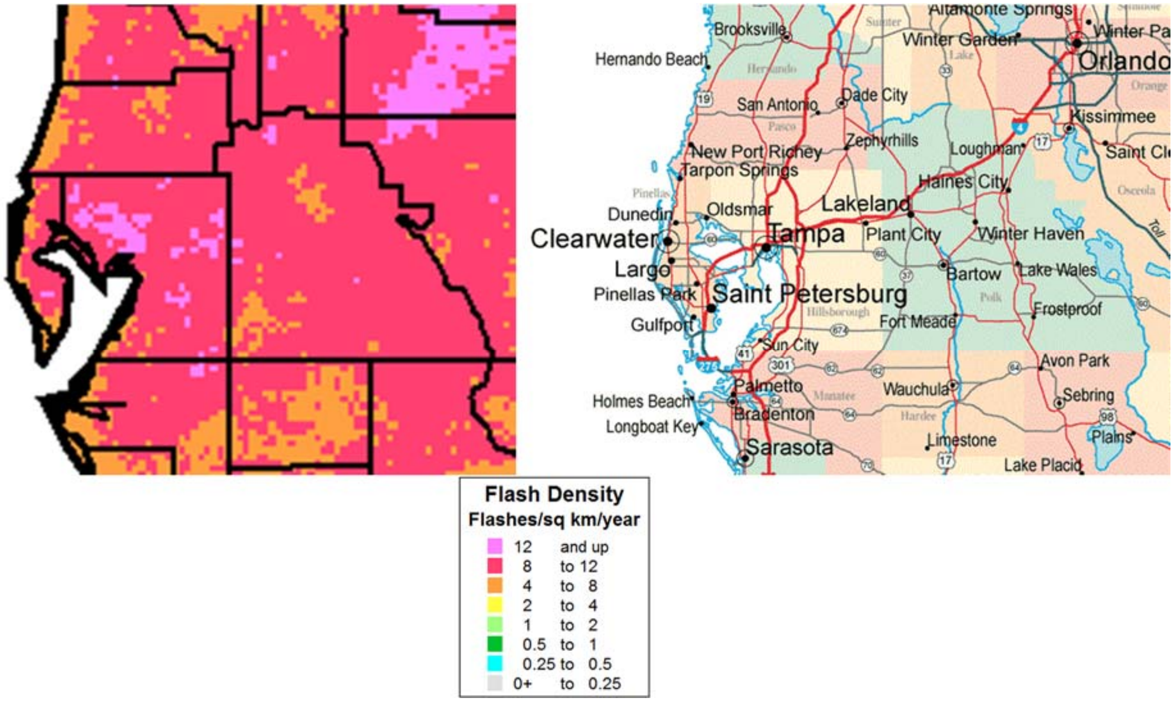


Figure 4.6. Lightning Flash Density and Highway Map for West Central Florida (Vaisala)

Assessment Method and Results

The first step in this assessment was to identify all the MVDS sites installed on 20 ft. concrete poles on I-4 between MM 3.5 and MM 54.1. Google Earth was used to visually identify these sites and to verify whether or not there was an air terminal installed at each site. The assessment of effectiveness and necessity of air terminals was conducted on 32 MVDS sites between MM 3.5 and MM 22.4 without air terminals, and 43 MVDS sites between MM 22.4 and MM 54.1 with air terminals installed.

TransCore, the ITS Maintenance Service contractor for District 7, provided the corrective maintenance reports for all MVDS installation on I-4 from June 2011 to May 2016 (5 years in all). The reports were filtered to reflect only the 75 sites being considered. Then each maintenance report was categorized “Visits no Damage”, “Non-Lightning Damage”, “Possible Lightning Damage”, and “Likely Lightning Damage” (see descriptions of the categories in Table 4.1). The count of maintenance reports in each category was recorded for each month separately for those site with air terminals and those site without air terminals.

CATEGORY	DESCRIPTION
Visits no Damage	Maintenance visit not requiring replacement or repairs. Does not Include power company/AT&T issues, testing, or planned replacements. Examples: dirty dome, tightened cable, went to sight no problems.
Non-Lightning Damage	Had to repair or replace something, not from electrical issue. Example: hit by car, vandalism, ants, etc.
Possible Lightning Damage	Any problem that could be associated with lightning. Examples: resetting UPS/radios, having to replace PTZ cable, replacing of video SPD, etc.
Likely Lightning Damage	Problem almost certainly caused by lightning. Examples: tripped breakers, burnt SPD/ fuse, replacing of SPD for power source

Table 4.1. Table of Work Order Categories Used for Assessment

The counts in each category were averaged over the five years of data for each month (January – December). Then the assessment focused on those maintenance reports that were categorized as either possible or likely lightning damage, and attempted to determine if there was a difference in the increase in lightning damage during the summer lightning months between those sites with air terminals and the sites without air terminals. Separately for the sites with and without air terminals, the sum of the average counts possible lightning damage and likely lightning damage in each month was divided by the total number of sites (43 sites with air terminals and 32 sites without air terminals) to determine the "% Possible & Likely Lightning Damage" per month. The results are plotted in Figure 4.7.

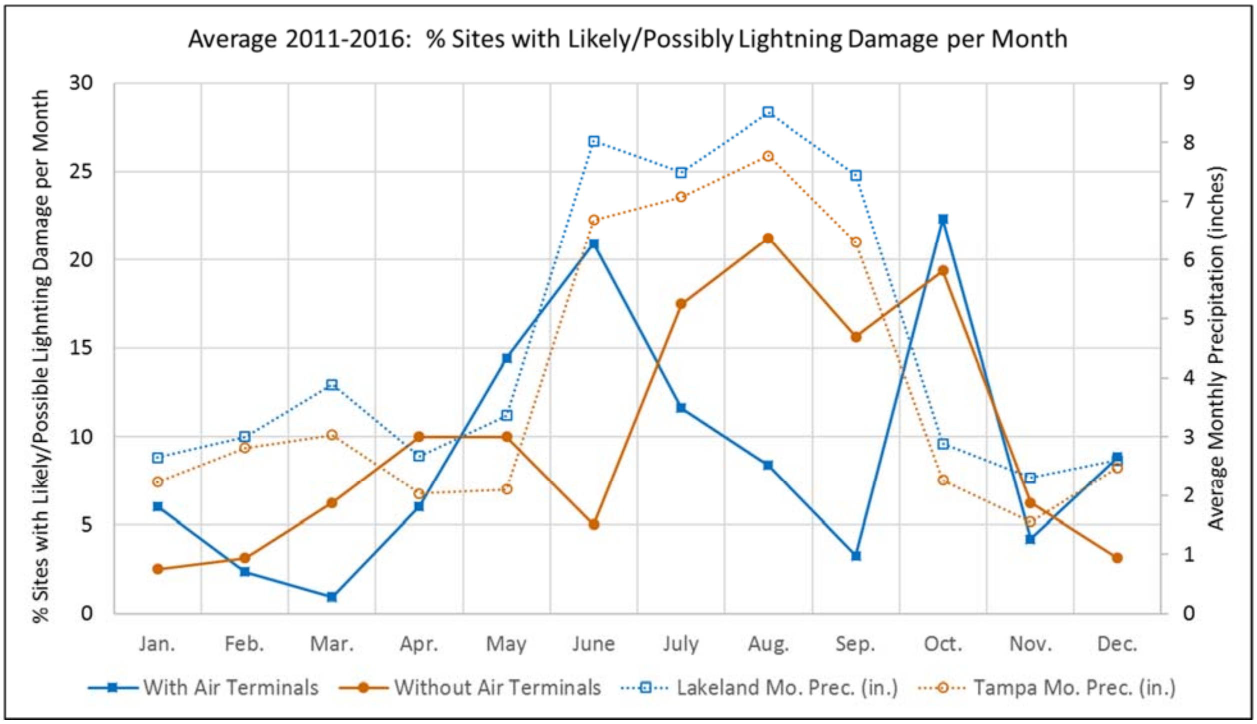


Figure 4.7. Average Percentage of Sites with Likely of Possible Lightning Damage Per Month

To determine which months in the summer are the most likely to have lightning, the 1981-2010 monthly average precipitation for Lakeland, FL (near the area of the sites *with* air terminals) and Tampa, FL (near the area of the sites *without* air terminals) was acquired from the NOAA website (http://www.ncdc.noaa.gov/cdo-web/datatools/normals). This data is also plotted in Figure 4.7. The average precipitation rates show that the peak summer precipitation (and thus peak lightning) months are June – September. Therefore, the % Possible & Likely Lightning Damage was averaged for the sites with and without air terminals during the peak lightning months of June – September. For comparison, the % Possible & Likely Lightning Damage was averaged for the low lightning months of December – March. Subtracting the averages for the low lightning months from that of the peak lightning months provides % Difference in increased % Possible & Likely Lightning Damage for site with air terminals. These results are tabulated in Table 4.2.

	Without Air Terminals	**With Air Terminals**	**% Difference**
Low Lightning Months: December - March	3.75%	4.53%	20.93%
Peak Lightning Months: June - September	14.84%	11.05%	-25.58%
Increase During Peak Lightning Months	11.09%	6.51%	-41.30%

Table 4.2. % Possible & Likely Lightning Damage for Peak and Low Lightning Months

The results in Table 4.2 appear to indicate that the inclusion of air terminals on the concrete MVDS poles is effective reducing the damage caused by lightning. During the low lightning months, the average % Possible & Likely Lightning Damage was 3.75% for site without air terminals and 4.53% for sites with air terminals. The sites with air terminals had an on 0.78% higher % Possible & Likely Lightning Damage than the sites without air terminals. However, during the peak lightning months the average % Possible & Likely Lightning Damage was 14.84% for sites without air terminals and only 11.05% for sites with air terminals. The sites with air terminals had a 25.58% lower % Possible & Likely Lightning Damage than did the sites without air terminals. Considering only the increase in average % Possible & Likely Lightning Damage during the peak lightning months, the sites with air terminals had 41.30% lower increase in % Possible & Likely Lightning Damage than did the sites without air terminals.

This forensic assessment of maintenance records to determine the effectiveness and necessity of air terminals does have some limitations and mitigating factors that must be considered. First, the test area is distributed over 50+ miles of I-4 and the lightning flash density (see Figure 4.6) varies across the test area. Most of this region has a flash density of 8 – 12 flashes/km^2/year, but there are locations in Hillsborough County (sites without air terminals) where the density is over 12, and locations within Polk County (sites with air terminals) where the flash density drops to 4 – 8. It is estimated that the average flash density for the sites with air terminals is 10 – 20% lower than the average flash density for the site without air terminals. This difference could account for half or more of the difference of the increase in % Possible & Likely Lightning Damage during the peak lightning months.

A second, more focused forensic assessment of the maintenance records was conducted using only the 6 MVDS sites without air terminals and the 6 MVDS sites with air terminals in close proximity to each other centered the Hillsborough/Polk County line. This is an 8-mile test area with relatively consistent lightning flash density. The results of this focused assessment indicated that the increase in average % Possible & Likely Lightning Damage during the peak lightning months was 68.42% lower for the site with air terminals than for the sites without air terminals. However, a closer review of the data revealed that this focused forensic assessment revealed only 42 total maintenance reports were classified as possible or likely lightning damage for these 12 sites over 5 years. In comparison, the results for the 75 MVDS sites included 253 total maintenance results for 75 sites over 5 years. This focused study again revealed a lower increase in lightning-related maintenance service for the site with air terminals, but the magnitude of the difference may be exaggerated due to statistical variance from the limited number of maintenance reports in the assessment.

Another mitigating factor concerning these results may be the age of the equipment at these MVDS sites. The TransCore personnel who provided the maintenance records indicated that many of the MVDS units and associated equipment are reaching the end of their serviceable life and are being replaced by newer model units when they fail. Therefore, some of the failures categorized as possible or likely lightning damage may be the result of a combination of age and summer heat. At the time of this report, the dates when these MVDS units were installed has not been provided.

Direct Lightning Strike

Air terminals are primarily designed to add protection from a direct lightning strike to the installation. In the 5 years of the maintenance review, only one site was indicated as having experienced an obvious direct lightning strike. The MVDS site eastbound on I-4 at MM 15.8 experienced a direct strike that caused significant structural and electronic damage (see pictures of some of the damage in Figure 4.8). This site did not have an air terminal. It appears that the reinforcing steel in the concrete column became the down conductor and the current arced to the attached cabinet and conduit support causing physical damage to the concrete pole. Also, the electronics within the cabinet was severely damaged.

There is no way of determining if other direct lightning strikes occurred at sites where the air terminals successfully grounded the current avoiding visible damage. However, this is the only direct strike reported by District 7 in any of the 32 sites without air terminals over the 5 years of maintenance data provided. Reliable statistics are not possible with only one incident, but this is an average of one direct strike per year for every 160 MVDS sites without air terminals.

Figure 4.8. Direct Lightning Strike Damage to MVDS site at MM 15.8 on I-4

4.2.3 Conclusions and Recommendations from Air Terminal Effectiveness Assessment

The results of the forensic maintenance assessment performed under this effort are not completely conclusive but the results do provide evidence that air terminals on MVDS installation may reduce the increase in maintenance required during the summer peak lightning months. It is interesting to note that the 20 ft. MVDS poles that were the focus of this assessment are among some of the shortest poles used for the installation of ITS sensor, traffic control and roadway lighting. If air terminals (or lightning termination to the structure) provide some benefit for these shorter poles/structures, it is logical to assume they would be of greater benefit for taller poles which are more susceptible to direct lightning strikes.

Air terminals are primarily designed to provide protection or damage reduction from a direct lightning strike. There was only one direct lightning strike reported and it was on a site that did not have an air terminal installed. The direct strike caused not only extensive electrical equipment damage but also extensive structural damage to the site. Given the current maintenance records it is not possible to determine if there were direct lightning strikes to the sites with air terminals because the air terminals and grounding may have mitigated or reduced the damage to the sites.

4.3 Conclusions and Recommendations for Task 3

The primary focus of this task was to review the effectiveness of lightning termination devices and to make recommendations for their use in ITS, traffic control and roadway lighting installations. The high flash density of lightning in the State of Florida makes proper protection from lighting surges and direct strike a necessity. Proper lightning protection systems will reduce the cost of maintaining the growing number of roadside installations of ITS, traffic control and roadway lighting systems.

This included two efforts: a review of the NFPA 780 standard, and a field test of roadside installation with and without air terminals. During the review of the NFPA780 standard, a second standard (recommendation) from the Telecommunications Standards Sector of the International Telecommunication Union (ITU-T) was found that had application to FDOT ITS, traffic control and roadway lighting installations. This standard is K.56 Protection of Radio Base Stations Against Lightning Discharges, and a review of this standard was added to the first effort. Also, no location was identified that could serve as an appropriate and cost-effective test site for conducting a field test of roadside installations with and without air terminals installed. Therefore, a forensic analysis of 5 years of maintenance records of MVDS sites on I-4 was used to assess the effectiveness and necessity of air terminals.

Although the primary effort on this task was focused on lightning termination and air terminals, the reviews in particular resulted in recommendations for 3 of the 4 parts of a standard lightning protection system. Therefore, the recommendations provided here include (1) lightning strike termination, (2) the conductor to ground and (3) grounding electrodes. The requirements for SPDs have been discussed in previous task reports and the requirements in these reviewed standards are very similar to the recommendations in those reports.

The ITU-T K.56 recommendations also include some concepts for bonding and shielding that may provide additional protection from lightning surges, particularly surges in power and signal (communication) cables that connect between cabinets and electronic equipment mounted on a pole or other elevated structure. These recommendations are also provided here and should be considered for future lightning protection installations for high-cost or safety-related equipment.

4.3.1 Recommendations for Lightning Strike Termination

1. The decision to include an air terminal for termination should be based on the following factors:
    a. The susceptibility of the structure to damage. Installations that are taller than surrounding structures, not protected by overhead lightning termination, and/or near water tend to be more susceptible to lighting strikes.
    b. The cost to repair or replace equipment and structure damaged by direct lightning strike. As demonstrated by the example of an MVDS concrete pole struck by lightning, damage can be very extensive to both equipment and structures if there is no proper lightning termination and grounding. However, a 20-foot concrete pole is less expensive that a 40-foot pole to replace and less likely to be struck by

        lightning. Also, the cost of the replacement of a DMS may warrant protection of the DMS itself with air terminals.
    c. The requirement, for safety or other reasons, for the reliable operation of the installation. Failure of critical roadway lighting and traffic control systems can adversely affect safety on the roadway and can warrant the additional expense of adding an air terminal or other lightning termination.
2. Static dissipaters (i.e., "witches broom") should not be used in place of an air terminal. No standard or recommendation reviewed for this project recommends static dissipaters for lighting protection and technical literature reviewed indicates the effectiveness of the dissipaters is minimal at best.
3. The angular method (up to 50' height) or the rolling sphere method (Section 2.1.1.3) should be used to determine the placement, number and length of air terminals.
4. Air terminal characteristics:
    a. Can be either sharp or blunt.
    b. Tip shall be not less than 10" above the structure protected.
    c. Minimum diameter: 3/8" (9.5 mm) if copper, 1/2" (12.7 mm) if aluminum.
    d. Wall thickness of tubular air terminals: 0.033" (0.8 mm) if copper, 0.064" if aluminum.
    e. Air terminals taller than 24" should be supported at mid height or of larger than minimum diameter and wall thickness if over 24". Diameter and thickness should be sufficient for the air terminal to endure the structural load of wind and pole swaying.
5. Any metallic body of a structure (pole) can be used for lightning terminations provided that it's thickness is at least 3/16". The angular method (up to 50' height) or the rolling sphere method (Section 2.1.1.3) should be used to determine the zone of protection provided by the structure.

4.3.2 Recommendations for Grounding Conductors

1. If practical, 2 or more grounding conductors, physically separated, should be used to connect the lightning termination device to the grounding or earthing system. Using multiple conductors reduced the inductive impedance of the grounding conducting system.
2. Ground conductors for structures up to 75 ft. in height:
    a. Copper cable conductors:
        i. Minimum cross-section area = 0.0451 in^2 (29 mm^2). In terms of the American wire gauge, the main conductors must be #2 AWG (0.0521 in^2 or 33.6 mm^2) or lower.
        ii. If stranded wire is used, then the size of each strand must have be #17 AWG or lower.
    b. Aluminum cable conductors:
        i. Minimum cross-section area = 0.0774 in^2 (50 mm^2). In terms of the American wire gauge, the main conductors must be #1/0 AWG (0.0829 in^2 or 53.5 mm^2) or lower.
        ii. If stranded wire is used, then the size of each strand must have be #14 AWG or lower.
    c. Copper strip conductors:

        i. Minimum thickness = 0.051 in. (1.3 mm).
        ii. Minimum cross-section area = 0.0451 in^2 (26 mm^2).
    d. Aluminum strip conductor:
        i. Minimum thickness = 0.064 in. (1.6 mm).
        ii. Minimum cross-section area = 0.0775 in^2 (50 mm^2).

3. Permanents metal framework of the structure can substitute for ground conductors provided the structure is:
    a. Electrically continuous.
    b. At least 0.1875 in. (4.8 mm) in thickness.
    c. Has a minimum cross-section area of at least 0.233 in^2 (150 mm^2).
4. For reinforced concrete columns, grounding (down) conductors shall be bonded to the reinforcing or structural steel in the column at both the top and bottom of the column.
    a. The bonding cables must be #6 AWG or lower if copper and #4 AWG or lower if aluminum.
    b. Bonding strips must have a minimum width of ½ in and a minimum thickness of 0.051 in (copper) or 0.064 in (aluminum).
5. Proper installation of grounding (down) conductors:
    a. Paths to the grounding electrodes shall be horizontal, downward (slight rising paths allowed up to a ¼ slope).
    b. Bends should be avoided where practical, but if needed bends should be no greater than 90 degrees and with a radius no less than 8 in.
6. Connections between air terminals, ground conductors, bonding conductors and grounding electrodes shall be secured by bolting, brazing, welding, screwing or high-compression connectors. NFPA requires the connections to withstand a 200 lb. (890 N) pull test

4.3.3 Recommendations for Grounding (Earthing) Electrodes

1. Grounding electrodes (rods) shall be:
    a. Made of copper, copper clad steel or galvanized steel.
    b. Have a minimum length of 8 ft. (2.4 mm) and a minimum diameter of 1/2 in. (12.7 mm).
    c. Driven or buried into the earth to a vertical depth of no less than 10 ft. (3 m).
    d. Connected to the grounding conductors using the shortest practical length of conductor.
2. Multiple grounding electrodes may be used to lower the ground resistance (e.g., in sandy soil). Installation multiple ground rods should be done adhering to the following requirements:
    a. All grounding electrodes shall be bonded together at a single point (common ground) no more than 12 ft. in elevation. This indicates that “daisy chaining” ground rods should be avoided.
    b. Grounding electrodes (rods) shall be separated by at least the sum of their driven depths, where practical.
    c. It is recommended that multiple ground rods be connected by ground loop conductors with the same requirements as the main grounding conductors. This recommendation is a requirement (NFPA 780) if the structure is over 60 ft. in height.

3. Concrete encased grounding electrodes can be used for new constructions using the requirements listed in Section 2.1.3.

4.3.4 Recommendations for Bonding and Shielding

These recommendations are derived primarily from the IUT-T K.56 recommendations. These recommendations may be impractical or too costly to implement in all roadside installations, but may be useful for reducing maintenance costs or improving reliability where reduced maintenance or greater reliability is needed.

1. All power and signal cables be shielded by either a continuous metallic duct or by using shielded cables.
    a. Metallic ducts shall be:
        i. Electrically continuous for its entire length.
        ii. Made of galvanized steel with a cross-section area not less than 0.025 in^2 (16 mm^2).
        iii. Bonded to the ground conductor (or grounding structure) at least at its upper end and also bonded to the earthing (grounding) system at the entrance to the structure or cabinet.
    b. Shielded cables shall:
        i. Have electrically continuous shielding over its entire length.
        ii. Be installed directly along the metallic structure (pole) or down conductor (without a metallic duct).
        iii. Be bonded to the ground conductor (or grounding structure) at least at its upper end and also bonded to the earthing (grounding) system at the entrance to the structure or cabinet.
    c. Unshielded cables installed without a metallic duct require SPDs at both end of the cable that are bonded to the grounding system.
2. Cabinets closely (within 10's of meters) located to poles (or elevated structures) should have bonded grounding (earthing systems) as shown in Figure 4.5 in Section 4.1.2.
    a. The cabinet and separate pole shall have separate grounding systems (earthing rings in Figure 4.5).
    b. The grounding systems shall be bonded using 2 or more conductors meeting the requirements for grounding conductors in Section 4.1.2.1.
    c. Power and signal (communications) cables between the cabinet and tower shall be shielded as required in recommendation 1 of this section.

5 Final Conclusions and Recommendations

The results from this project include a number of recommendations for improving lightning protection systems and components for the protection of ITS, traffic control, and roadway lighting equipment from transient surge and lightning strikes. Implementation of these recommendations will reduce the damage to roadside equipment by lightning strikes and surges, and provide the information to more effectively assess the actual damages that are caused by lightning.

Recommendation 1: Provide statewide minimum lightning protection standards for all roadside installations.

The results of the Florida district survey revealed similar increases in lightning damage during peak lightning months. Also, the lightning flash density average across the state (from Vaisala[2]) showed that the flash density was high in all parts of the state of Florida, ranging from 4 to over 14 lightning flashes per square kilometer per year. Considering that most of the districts use the same standards for ITS surge protection, it is possible that improving and standardizing surge protection measures further can provide additional savings in maintenance costs statewide.

Recommendation 2: Use the standard IEEE combination waveform (1.2/50 μs voltage / 8/20 μs current) to evaluate and approve the performance of SPDs used in ITS installation in Florida.

Based on the research conducted in Effort 1 of Task 2, it is recommended that the standard combination waveform (1.2/50 μs voltage / 8/20 μs current) used to evaluate and approve the performance of SPDs used in ITS installation in Florida shall be continued. The SPDs should be tested not only for verification of peak current capability, but also for the capability of the SPD to endure multiple surges.

The equipment necessary to create an SPD acceptance/performance test lab for the FDOT was identified, acquired, and assembled. The primary equipment specified and acquired was (1) a MIG0606 Current Tester fitted with the TC-MIG24ED, commercially available from EMC Partner AG and (2) a Tektronix MDO3024 Mixed Domain Oscilloscope. Using this equipment, the FDOT can test an SPD with up to a 6-kV open-circuit voltage / 6-kA short-circuit current. Test procedures are identified to perform acceptance and performance testing of SPDs.

Recommendation 3: Test SPDs for both initial performance and resilience.

Initial performance tests (procedure detailed in Section 3.2.3.1) are used to determine primarily the peak let-through voltage, the clamping voltage, and the response time of the SPD. Note that the response time of an SPD tends to be fairly consistent with respect to surge current/voltage over the operating range of the SPD. The peak let-through voltage depends not only on the response time, but also on the initial slope of the surge voltage (volts per microsecond), which varies with the magnitude of the surge. Peak let-through voltage can only be specified for a particular peak voltage test waveform. Additionally, the clamping voltage for a particular application of the SPD should be specified to be greater than the maximum operating voltage but not greater than the maximum rated voltage for the device(s) protected.

Resilience testing (procedure detailed in Section 3.2.3.2) determines the ability of an SPD to protect the electronic equipment from multiple (or many) lightning surges.

Based on the field tests it was recommended that SPDs for the in-pavement sensors have a peak current capability of 10 – 20 kA and that the SPD be capable of enduring at least 5,000 surges with a peak current of 6 kA. This recommendation is a good starting point for determining an appropriate Florida FDOT specification for the number and magnitude of surges that the low-voltage SPDs are required to endure.

Recommendation 4: Improve and standardize the template for maintenance reporting for ITS and other FDOT roadside installations.

A survey and assessment was conducted of the current maintenance and reporting procedures used for supporting ITS equipment in the various FDOT districts in Florida. It was determined that these functions were generally being conducted by contractors and the methods, level of detail and data collected varied by district. It is recommended that a standard template for ITS maintenance reporting be defined and that all districts be required to include the template in contracts for ITS maintenance. This process will provide the FDOT the capability to monitor and evaluate lighting protection strategies and equipment across the state.

It is recommended that the standard template for ITS maintenance include the following:

1. Location of the site where the failure occurred
2. Date and time of the equipment failure
3. Likelihood that damage caused by lightning according to a standard scale such as:
    a. Very Likely Due to Lightning
        i. Visible evidence of large current surges
        ii. Damage to SPD, fuse/breaker tripped, or other obvious indications of lightning surges
        iii. Known significant lightning activity at the time of the failure
    b. Possibly Due to Lightning
        i. Electronic failures with no other cause evident
        ii. Cable or wires requiring replacement with no evidence of cause for failure
        iii. Resetting or restarting equipment
        iv. Lightning activity in the area at time of failure
    c. Unlikely to be Due to Lightning
        i. Damage not due to electrical problem (e.g., water intrusion, vehicle accident, vandalism, insect intrusion)
        ii. No or very little lightning at the time of the failure
    d. Maintenance Not Damage-Related (i.e., regularly schedule maintenance)

        i. Regular maintenance (e.g., clean camera domes, calibration)
        ii. Upgrades or testing
        iii. Not related to ITS equipment
        iv. No maintenance required upon inspection

5. Equipment replaced as part of the repair including
    a. Type of equipment (e.g., SPD, communication, lighting, power, cable/wire)
    b. Description, model number
    c. Cost of the equipment
    d. Visual description of damaged or replaced equipment
6. Total cost of the maintenance required
    a. Equipment or components replaced
    b. Technician effort
    c. Vehicle or other equipment rental/costs
    d. Other related costs

Recommendations 5: Recommendations for lightning protection system design.

The review of NFPA 780 standard and the ITU-T Recommendation K.56 resulted in recommendations for the FDOT to incorporate into standards for all 4 components of lightning protection: (1) lightning strike termination, (2) grounding conductors, (3) grounding (earthing) electrodes and (4) bonding and shielding. This recommendation summarizes the recommendations for each of these 4 components.

Recommendations for Lightning Strike Termination

1. The decision to include an air terminal for termination should be based on the following factors:
    a. The susceptibility of the structure to damage. Installations that are taller than surrounding structures, not protected by overhead lightning termination, and/or near water tend to be more susceptible to lighting strikes.
    b. The cost to repair or replace equipment and structure damaged by direct lightning strike. As demonstrated by the example of an MVDS concrete pole struck by lightning, damage can be very extensive to both equipment and structures if there is no proper lightning termination and grounding. However, a 20-foot concrete pole is less expensive that a 40-foot pole to replace and less likely to be struck by lightning. Also, the cost of the replacement of a DMS may warrant protection of the DMS itself with air terminals.
    c. The requirement, for safety or other reasons, for the reliable operation of the installation. Failure of critical roadway lighting and traffic control systems can

adversely affect safety on the roadway and can warrant the additional expense of adding an air terminal or other lightning termination.

2. Static dissipaters (i.e., “witches broom”) should not be used in place of an air terminal. No standard or recommendation reviewed for this project recommends static dissipaters for lighting protection and technical literature reviewed indicates the effectiveness of the dissipaters is minimal at best.
3. The angular method (up to 50’ height) or the rolling sphere method (Section 2.1.1.3) should be used to determine the placement, number and length of air terminals.
4. Air terminal characteristics:
    a. Can be either sharp or blunt.
    b. Tip shall be not less than 10” above the structure protected.
    c. Minimum diameter: 3/8” (9.5 mm) if copper, 1/2” (12.7 mm) if aluminum.
    d. Wall thickness of tubular air terminals: 0.033” (0.8 mm) if copper, 0.064” if aluminum.
    e. Air terminals taller than 24” should be supported at mid height or of larger than minimum diameter and wall thickness if over 24”. Diameter and thickness should be sufficient for the air terminal to endure the structural load of wind and pole swaying.
5. Any metallic body of a structure (pole) can be used for lightning terminations provided that it’s thickness is at least 3/16”. The angular method (up to 50’ height) or the rolling sphere method (Section 2.1.1.3) should be used to determine the zone of protection provided by the structure.

Recommendations for Grounding Conductors

1. If practical, 2 or more grounding conductors, physically separated, should be used to connect the lightning termination device to the grounding or earthing system. Using multiple conductors reduced the inductive impedance of the grounding conducting system.
2. Ground conductors for structures up to 75 ft. in height:
    a. Copper cable conductors:
        i. Minimum cross-section area = 0.0451 in^2 (29 mm^2). In terms of the American wire gauge, the main conductors must be #2 AWG (0.0521 in^2 or 33.6 mm^2) or lower.
        ii. If stranded wire is used, then the size of each strand must have be #17 AWG or lower.
    b. Aluminum cable conductors:
        i. Minimum cross-section area = 0.0774 in^2 (50 mm^2). In terms of the American wire gauge, the main conductors must be #1/0 AWG (0.0829 in^2 or 53.5 mm^2) or lower.
        ii. If stranded wire is used, then the size of each strand must have be #14 AWG or lower.
    c. Copper strip conductors:
        i. Minimum thickness = 0.051 in. (1.3 mm).
        ii. Minimum cross-section area = 0.0451 in^2 (26 mm^2).
    d. Aluminum strip conductor:
        i. Minimum thickness = 0.064 in. (1.6 mm).

    - ii. Minimum cross-section area = 0.0775 in^2 (50 mm^2).
3. Permanents metal framework of the structure can substitute for ground conductors provided the structure is:
    - a. Electrically continuous.
    - b. At least 0.1875 in. (4.8 mm) in thickness.
    - c. Has a minimum cross-section area of at least 0.233 in^2 (150 mm^2).
4. For reinforced concrete columns, grounding (down) conductors shall be bonded to the reinforcing or structural steel in the column at both the top and bottom of the column.
    - a. The bonding cables must be #6 AWG or lower if copper and #4 AWG or lower if aluminum.
    - b. Bonding strips must have a minimum width of ½ in and a minimum thickness of 0.051 in (copper) or 0.064 in (aluminum).
5. Proper installation of grounding (down) conductors:
    - a. Paths to the grounding electrodes shall be horizontal, downward (slight rising paths allowed up to a ¼ slope).
    - b. Bends should be avoided where practical, but if needed bends should be no greater than 90 degrees and with a radius no less than 8 in.
6. Connections between air terminals, ground conductors, bonding conductors and grounding electrodes shall be secured by bolting, brazing, welding, screwing or high-compression connectors. NFPA requires the connections to withstand a 200 lb. (890 N) pull test

Recommendations for Grounding (Earthing) Electrodes

1. Grounding electrodes (rods) shall be:
    - a. Made of copper, copper clad steel or galvanized steel.
    - b. Have a minimum length of 8 ft. (2.4 mm) and a minimum diameter of 1/2 in. (12.7 mm).
    - c. Driven or buried into the earth to a vertical depth of no less than 10 ft. (3 m).
    - d. Connected to the grounding conductors using the shortest practical length of conductor.
2. Multiple grounding electrodes may be used to lower the ground resistance (e.g., in sandy soil). Installation multiple ground rods should be done adhering to the following requirements:
    - a. All grounding electrodes shall be bonded together at a single point (common ground) no more than 12 ft. in elevation. This indicates that “daisy chaining” ground rods should be avoided.
    - b. Grounding electrodes (rods) shall be separated by at least the sum of their driven depths, where practical.
    - c. It is recommended that multiple ground rods be connected by ground loop conductors with the same requirements as the main grounding conductors. This recommendation is a requirement (NFPA 780) if the structure is over 60 ft. in height.
3. Concrete encased grounding electrodes can be used for new constructions using the requirements listed in Section 4.1.1.3.

Recommendations for Bonding and Shielding

These recommendations are derived primarily from the IUT-T K.56 recommendations. These recommendations may be impractical or costly to implement in all roadside installations, but may be useful for reducing maintenance costs or improving reliability where reduced maintenance or greater reliability is needed.

1. All power and signal cables be shielded by either a continuous metallic duct or by using shielded cables.
    a. Metallic ducts shall be:
        i. Electrically continuous for its entire length.
        ii. Made of galvanized steel with a cross-section area not less than 0.025 in^2 (16 mm^2).
        iii. Bonded to the ground conductor (or grounding structure) at least at its upper end and also bonded to the earthing (grounding) system at the entrance to the structure or cabinet.
    b. Shielded cables shall:
        i. Have electrically continuous shielding over its entire length.
        ii. Be installed directly along the metallic structure (pole) or down conductor (without a metallic duct).
        iii. Be bonded to the ground conductor (or grounding structure) at least at its upper end and also bonded to the earthing (grounding) system at the entrance to the structure or cabinet.
    c. Unshielded cables installed without a metallic duct require SPDs at both end of the cable that are bonded to the grounding system.
2. Cabinets closely (within 10's of meters) located to poles (or elevated structures) should have bonded grounding (earthing systems) as shown in Figure 4.5 in Section 4.1.2.
    a. The cabinet and separate pole shall have separate grounding systems (earthing rings in Figure 4.5).
    b. The grounding systems shall be bonded using 2 or more conductors meeting the requirements for grounding conductors in Section 4.1.2.1.
    c. Power and signal (communications) cables between the cabinet and tower shall be shielded as required in recommendation 1 of this section.

6 Benefits to the FDOT

It is anticipated that the recommendations presented in this final report will provide the following benefits to the Florida Department of Transportation (FDOT):

1. Recommendations for test equipment and test procedures to develop a surge protective device (SPD) test laboratory at the FDOT-TERL. This will allow the TERL to validate current SPD specifications in-house and conduct acceptance testing for SPDs that are currently listed, or submitted for listing, on the FDOT Approved Product List (APL). Improved acceptance specifications/testing will lead to more robust/resilient surge protective device, which will reduce maintenance calls and replacement costs.
2. Recommendations for a standard statewide maintenance template to be used by ITS maintenance personnel. This will provide information needed to more accurately assess the effects of lightning on ITS roadside equipment. The improved assessment data will allow the FDOT to efficiently utilize lightning surge protection measures and ultimately reduce maintenance costs.
3. Recommendations for the design of lightning protection systems for FDOT roadside equipment including ITS, traffic control and roadway lighting systems. Based on these recommendations, guidelines can be developed that would allow FDOT to reduce design and build costs by including only the most appropriate and cost effective lightning protection measures, and by improving the lightning protection systems for the most vulnerable and/or costly installations.