FINAL REPORT

IMPROVING OPERATION OF FDOT TELEMETERED TRAFFIC MONITORING SITES

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SUBMITTED BY:

FAMU-FSU College of Engineering
Florida State University
2525 Pottsdamer Street
Tallahassee, FL 32310-6046

PRINCIPAL INVESTIGATOR:

Bruce A. Harvey, Ph. D.
Assistant Professor
Department of Electrical and Computer Engineering
Phone: (850) 410-6451
Fax: (850) 410-6479
Email: bharvey@eng.fsu.edu

CO-PRINCIPAL INVESTIGATOR:

Renatus Mussa, Ph.D., P.E.
Assistant Professor
Department of Civil and Environmental Engineering
Phone: (850) 410-6191
Fax: (850) 410-6142
Email: mussa@eng.fsu.edu

FOR:

Florida Department of Transportation
Transportation Statistics Office

Prepared in cooperation with the State of Florida Department of Transportation.

Executive Summary

The Florida Department of Transportation (FDOT) currently monitors about 7,000 traffic count sites including over 300 permanent Telemetered Traffic Monitoring Sites (TTMSs). The monitoring equipment generally consists of traffic-actuated sensing devices imbedded in the pavement that captures the information traffic volumes, vehicle classification, and truck weights. The information captured by the field monitoring devices is thereafter downloaded and processed to get information on Annual Average Daily Traffic (ADT), K-factor, T-factor, truck weight, and other pertinent information. This information is used in various forms by different FDOT departments for planning, designing, operations, and maintenance activities relating to both highway pavements and bridges.

The FAMU-FSU College of Engineering (COE) was contracted to provide support to the Transportation Statistics Office (TSO) of the FDOT in improving the accuracy and reliability of the TTMS sensors and communication equipment. The Principal Investigator for the project was Dr. Bruce A. Harvey of the Department of Electrical and Computer Engineering. The Co-Principal Investigator was Dr. Renatus Mussa of the Department of Civil and Environmental Engineering. The project was conducted from April 30, 2000 to September 30, 2003. The major efforts conducted under this project were

1. Cellular Communication Improvement for Site 9936,
2. Modem Performance Study,
3. Telephone Line Surge Protection,
4. Evaluation of Bonding Materials Used in Piezoelectric Axle Sensor Installation, and
5. Mining of Florida ITS Data for Transportation Planning.

In addition to the major efforts, the COE also provided technical support for the TSO as needed throughout the project.

The cellular communication improvement for site 9936 (located on I-10 about 8 miles east of the intersection of US-441 at the CR-250 overpass) was initiated to correct poor or nonexistent cellular communication. FDOT personnel had to manually download information at this weigh-in-motion (WIM) site. Solving this problem involved research on available cellular carriers and towers, on-site investigations and tests, replacement of a directional cellular antenna, and changing the cellular provider to improve service and performance. The efforts under this task were successful in improving the reliability of the communications with the cellular modem at site 9936. Several recommendations on cellular site installations resulted from this effort. These recommendations include use and proper installation of high-gain directional antennas to improve signal power, use of low-loss cable between the antenna and the cellular transceiver, identifying the best cellular provider (generally 2 available in most locations) by locating their nearest tower, and obtaining assistance from the cellular provider in aiming the directional cellular antenna.

The modem performance study was performed to mitigate the observed communication problems between the modems in the over 300 TTMS sites and the data collection modems in the FDOT Burns Building. Typical problems include inability to communicate, slow connection speeds, frequent drop of signals and data errors during transmission. The goal of this task was to determining the causes for the poor performances and the apparent incompatibilities between certain modems. The research effort included surveying available DC-powered modems including specifications, communication protocols supported and manufacturer's chipset; conducting tests on the modems to quantify performance differences between modems for the purpose of defining specifications for future modem purchases; and examining modem strings defined by the traffic monitoring equipment manufacturers for use on particular modems. The results of the analysis and testing performed included the following recommendations and specifications:

- Protocols and Operating Speeds: Modems speed should be 14.4K (V.32bis), 28.8K (V.34) or 33.6K (V.34bis). Avoid the use of 56K modems.
- Communication Performance: Test each modem considered to ensure that it can connect with the FDOT data collection modems with white noise levels of at least 55 dBrn (-35 dBm), and also it can connect with attenuation levels of at least 28 dB. Test procedures are provided.
- Data Compression and Specialized Protocols: The V.42bis compression protocol is preferred over MNP 5. Cellular protocols (MNP 10, MNP 10EC and MNP 10 ETC) are non-standard and should generally be used only for cellular applications and only with compatible modems.
- Initialization Strings: Modems should be reset to factory defaults before configuration. Then the minimum number of commands added to the string (do not repeat defaults) to set the modem to answer when called, disable software flow control, enable any special function required by the TTMS equipment manufacturer, and enable cellular-specific protocols if needed.

Test procedures have been developed to verify the Communication Performance specifications listed above. These tests should be conducted on each pair of modem types anticipated to be used to communicate with the TTMS sites.

Telephone line surge suppressors protect the modem and other equipment in the TTMSs for current surges on the telephone lines generated by lightning in the immediate area. Telephone lines are generally more vulnerable to lightning surges than sensor or solar power lines entering the TTMS cabinets due to their long lengths offering greater opportunity for induced or direct strike surges. Historically, the existing surge suppressors have been successful at protecting the equipment, but the suppressors have often been damaged or destroyed by these surges. Replacing the surge suppressors is expensive, especially in terms of manpower, and the TTMS data cannot be collected until the suppressor has been replaced. The goal of this task was to determine the appropriate specifications and test procedures for identifying surge suppressors that will protect the equipment in the TTMS cabinets from telephone line surges, and will be resilient to surge suppressor failures. The effort included research on surge suppressor, analysis of failed surge suppressors, field measurements to ascertain surge environment and testing of available telephone line suppressors. It was found that the number of current surges rather than high current direct lightning strike was the primary cause of suppressor failures. Test procedures were developed and the following telephone line surge suppressor specifications were recommended:

- Peak Surge Capability: minimum of 10,000 Amps
- Resiliency: 10,000 surges of magnitude 6,000 Amps (IEEE 8/20 μsec waveform)
- Maximum Operating Voltage: 150 – 200 Volts
- Clamping: Output Voltage clamped to below 200 Volts within 10 microseconds
- Potting: The electronics contained in the surge suppressor should be potted, sealed in epoxy or otherwise sealed.
- Connectors: Telephone Line Side: Solid mechanical connectors such as spade lugs with washers.
- Modem Side: RJ-11 modular telephone line jack and minimum 5' RJ-11 cable for connecting to the modem.

The evaluation of bonding materials used in piezoelectric axle sensor installation was conducted to develop test procedures that can be used to test the piezoelectric axle sensor adhesives. In addition, this research was also aimed at developing material specifications that will be used to select adhesives to achieve long-term field performance of piezoelectric axle sensors suitable for Florida traffic, pavement, and environmental conditions. The goal is to reduce failures of piezos at TTMSs reducing the high cost of replacements and the attendant disruption of traffic flow. This effort included a comprehensive literature search on the characteristics of epoxies, acrylics, and polyurethanes; a survey of the experience of State DOTs in the U.S. on the use of these adhesives for piezo installations; laboratory testing of the approved adhesives; and long-term field monitoring of ANOVA-designed experiments.

Based on the results of this effort it is recommended that the Florida Department of Transportation use acrylic-based adhesives with increasing frequency in the installation of piezoelectric axle sensors in asphalt concrete pavements. Though there are only two acrylic-based adhesives currently approved by FDOT, i.e., IRD AS475 and ECM P5G, it is recommended that P6G, the modified product of P6G be included in the Florida Department of Transportation approved list of adhesives. It is also recommended that a monitored field test be conducted on E-Bond 1261, the only epoxy-based material that had a number of properties that may be suitable for installation of piezoelectric axle sensors in asphalt concrete pavements.

The mining of Florida ITS data for transportation planning effort was undertaken to determine the efficacy of using ITS data for transportation planning purposes. The Transportation Planning Statistics Office recently commissioned a pilot project study on site 750196 at station 36 on I-4 corridor in Orlando. The study was able to convert ITS data at this station through a simple Oracle SQL-based computer routine. The data was converted from minute averages of volume and speed to hourly summaries of volumes and speeds for each lane in both directions at this site. Thus, the objective of this effort was to build upon the positive results of this pilot project and to develop a mechanism that can be used statewide to capture and convert ITS data into a format compatible with that of TTMS and temporary count sites. This effort consisted of a literature search for similar efforts in other locations, a study of the Orlando ITS network configuration, the installation of a data capture computer in Orlando, and the development of a program to capture the useful data. The outcome of this pilot project has shown that it is possible to extract planning-compatible traffic data from loops installed on freeways for incident surveillance and other ITS purposes. The FDOT District V Planning Office is currently able to download traffic data composed of hourly volumes from several sites along the Interstate 4 corridor. Because of this effort of this project, it was expected that the Florida Department of Transportation would potentially save $200,000 by foregoing the installation of new loops for collecting planning data in areas that ATMS loops already exist on I-4. With the expansion of ITS activities along Interstate 4 corridor, additional sites will be incorporated thus reducing the need to install TTMS sites along the corridor leading to additional savings.

All of the tasks conducted under this project were successfully completed by the faculty, staff and student of the FAMU-FSU College of Engineering.

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1. Introduction

The Florida Department of Transportation (FDOT) currently monitors about 7,000 traffic count sites including over 300 permanent Telemetered Traffic Monitoring Sites (TTMSs). The monitoring equipment generally consists of traffic-actuated sensing devices imbedded in the pavement that captures the information traffic volumes, vehicle classification, and truck weights. The information captured by the field monitoring devices is thereafter downloaded and processed to get information on Annual Average Daily Traffic (ADT), K-factor, T-factor, truck weight, and other pertinent information. This information is used in various forms by different FDOT departments for planning, designing, operations, and maintenance activities relating to both highway pavements and bridges.

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2. Modem Performance Study,
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In addition to the major efforts, the COE also provided technical support for the TSO as needed throughout the project.

2. Cellular Communication Improvement for Site 9936

Summary of Objectives

The telemetered traffic data collection site 9936 is located on I-10 about 8 miles east of the intersection of US-441 at the CR-250 overpass. That location presents unique communication problems since it is located in the Osceola National Forest. Restrictions on installation of utilities required that communication with the site be conducted via wireless means. Hence, a cellular modem and cell phone was installed at the site and cellular service was contracted with Alltel. Unfortunately, since the installation of the site there has never been a consistent ability to download the data collected via the cellular modem. This problem is exacerbated by the fact that site 9936 is a weigh-in-motion (WIM) site which collects data files over 300 Kbytes each day. Technicians have had to manually download the data.

Prior to the start of this project, the cellular communication problem was addressed in multiple ways including the installation of a directional antenna on a utility pole located on CR-250 at the edge of the overpass. However, the cellular communication was still inconsistent and FDOT personnel were required to download the data manually at the site on a weekly basis (the limit of the memory of the equipment).

The efforts under this project period of performance focused on evaluating the available cellular communication options, investigating the characteristics and performance of cellular modem communication, on-site investigations, and establishment of more reliable cellular communications. These efforts are summarized below.

Activities Conducted

A review of all commercial cellular and PCS communication providers in the area of site 9936 was conducted. The only operational PCS provider was SPRINT, but communication at the site using a SPRINT PCS phone was found to be no better than analog. Also, discussions with SPRINT representatives revealed that dial-in modem service is currently unavailable. A search of the Federal Communication Commission (FCC) web site reveled that the analog cellular providers for the location of site 9936 were Alltel and Cellular One. Alltel, the current cellular provider, has its nearest cellular tower located approximately 11 miles from site 9936 just south of Lake City. Conversations with Alltel representatives revealed that they would not guarantee data communication over their service and offered no further help. Cellular One however has its nearest tower located 8 miles from site 9936 just north of I-10 on US-441. Cellular One offered technical support and a free trial service to determine if they could provide more consistent communication with the site.

A literature search was conducted to determine the practical performance pitfalls of cellular data communication and to identify equipment settings required to optimize the performance. Wireless communication characteristics were studied including service area boundaries of cellular towers as defined by the Code of Federal Regulations (CFR) Chapter 47 Part 22. The CFR boundaries for both the Alltel and Cellular One towers were calculated to be a circle of approximately 11-mile radius. This put site 9936 on the very edge of the service area for the nearest Alltel cellular tower and within the range of Cellular One's nearest tower.

Multiple visits to site 9936 were conducted to analyze and repair the cellular communications problems. The cabling to the cellular antenna was found to be of a very low-loss variety and the elevated location of the antenna good. However, the antenna was found to be damaged on initial installation and was replaced. Support for correcting the problem was provided by a Cellular One technician, a technician from Santa Fe Technologies and a FDOT technician. A cellular phone borrowed from Cellular One was installed in place of the existing cellular phone and a trial period was started to determine if a new cellular provider can improve the performance. With the assistance of the Cellular One technician, the antenna was aligned for maximum signal strength. Cellular One provided temporary service to the site and tests confirmed that the communication was working. After the appropriate paperwork was completed, Cellular One was contracted to provide the cellular service. The cellular communication and data downloading was reliably working and this task was considered completed.

Results and Conclusions

The efforts under this task were successful in improving the reliability of the communications with the cellular modem at site 9936. Several recommendations also resulted from the efforts under this task that will assist the FDOT in the installation of cellular communications for other TTMSs. The recommendations are:

1. Use higher gain directional antennas to improve signal levels. The antennas are adjusted at the manufacturer and care should be taken not to modify the adjustments or damage the antenna.

2. Mount the antenna at the highest practical point, and away from metal and other dense objects.

3. Use low-loss cable to connect the cellular phone to the antenna. Minimize the use of cable adaptors as these increase losses.

4. Get the support of the cellular provider when aiming the directional antenna. The signal level indicator on a cellular phone is unreliable. Also there are typically two independent cellular providers in each area and the antenna must be directed towards tower of the cellular provider contracted. Also, if obstructions (trees, buildings, etc.) are present, the best pointing angle may not be directly towards the cellular tower.

5. In remote locations it may be necessary to contact the local cellular providers and/or search the Federal Communication Commission (FCC) web site to determine the provider with the closest tower to the TTMS.

A summary of this project was published in the winter 2001 issue of the FDOT publication "Research Today." The draft text for the article is provided in Appendix A. The article was written by J. Darryll Dockstader, Technology Transfer Manager, Research Center, Florida Dept of Transportation, (850) 414-4613.

3. Modem Performance Study

Summary of Objectives

Telephone line modems are the main vehicle used to collect traffic data from the over 300 Telemetered Traffic Monitoring Sites (TTMSs) currently in use by the Florida Department of Transportation (FDOT). Most of the TTMSs sole source of power is 12 Volt solar panels and thus the modems used in the field must operate on 12 Volts DC and draw very little power. Historically it has been observed that some of the DC modems used in the TTMSs and some of the standard desktop modems used for data collection do not perform as well as is expected. Typical problems include inability to communicate, slow connection speeds, frequent drop of signals and data errors during transmission.

The goal of this task was to determining the causes for the poor performances and the apparent incompatibilities between certain modems. In addition, the task called for the development of specifications and validation test procedures to mitigate the performance and incompatibility problems in future modems. The research efforts was divided into three primary tasks: (1) Conduct a survey of available DC modems including specifications, communication protocols supported and manufacturer's chipset; (2) Acquire a sample of modems (DC and desktop) and a telephone line emulator, and conduct performance tests on the modems to quantify performance differences between modems for the purpose of defining specifications for future modem purchases; and (3) Examine the modem strings defined by the traffic monitoring equipment manufacturers for use on particular modems.

Activities Conducted

The survey of DC modems identified modems ranging in top speeds of 33,600 to 2,400 bits per second (bps). Most could operate on 12 Volts DC while some could operate on as little as 5 or 9 Volts DC. Some of modems had sleep modes allowing lower power requirements. Included in the survey results were a few modems that had specialty protocols for handling wireless (cellular) links including MNP 10 and MNP 10EC. Cellular-specific modems however were not directly addressed in this study. All of the DC modems found operated using either the Covenant (formerly Rockwell) chipset or the Motorola chipset. Desktop modems were found using Covenant, Lucent and US Robotics chipsets. The specifications for the modems indicated that any pair of the modems found should be able to operate together across a telephone line. The handshaking protocols allow the modems to negotiate the best protocols available in both modems.

A Teltone TLE-A01 telephone line emulator was acquired to test the compatibility and performance of various pairs of modems. A total of eight (8) DC modem types and four (4) desktop modem types were acquired for testing in this phase of the project. Using the TLE-A01, pairs of modems were evaluated in the presence of ideal line conditions, signal attenuation, noise and combinations of impairments. Under ideal line conditions it was found that all pairs of modems could successfully negotiate parameters and transfer data; thus the modems were all essentially "compatible." During noise impairment tests, most modem pairs were able to connect and communicate with added noise levels up to 55 to 60 dBrn (-35 to -30 dBm). Most modem pairs with more susceptibility to noise included desktop modems with top speeds of 56 kbps; this is likely due to optimization of the modems for Internet dialup speeds. Telephone line attenuation test demonstrated that all modems operated with line attenuations up to 24 – 34 dB. Unlike the noise tests, there was no strong correlation between modem maximum speeds maximum line attenuation. Modem pairs that operate consistently with attenuations of 30 dB or more will likely operate well in the field. Combination of impairment tests confirmed that 56K modems are more sensitive to noise when communicating with 14,400 or lower speed modems.

Modem strings used to specify the operating parameters of the data collection modems have been a particularly vexing problem for the FDOT. Generally, the manufacturer of the traffic monitoring equipment specifies the modem strings for each modem type. Investigations of the modem strings currently in use found them to be overly complex. Often the strings repeated almost universal modem default conditions, and enabled or disabled features that were overridden by other commands.

Results and Conclusions

The results of the analysis and testing performed included a number of recommended specifications. These recommendations are as follows:

Protocols and Operating Speeds:

- Modems speed: 14.4K (V.32bis), 28.8K (V.34) or 33.6K (V.34bis).
- Generally 56K modems should be avoided.
- DC modems should operate at their highest available speeds.

Communication Performance:

- Each modem purchased must be able to connect with equal (same in both directions) white noise levels of at least 55 dBrn (-35 dBm).
- Each modem purchased must be able to connect and operate with equal attenuation levels of at least 28 dB.
- These specifications must be met when communicating with data collection modems used at the FDOT.

Data Compression and Specialized Protocols:

- V.42bis has better compression ratios than MNP 5 and should be preferred.
- MNP 10, MNP 10EC and MNP 10 ETC are protocols specifically designed for cellular communication. These are not standards however and have limited usefulness for wired modems. Thus they should be generally avoided or disabled.

Initialization Strings:

- Modems should be reset to factory defaults before configuration. (It is recommended to store in profile 0 as well.)
- Modems at the TTMS locations need to be configured to answer the phone when it rings (e.g. 'ATS0=1').
- Systems that transfer binary files need to ensure that software flow control is disabled; this is default in all modems tested.
- Special functions such as power saving or cellular protocols need to be enabled.
- Repeating factory defaults in the modem string should be avoided to reduce errors.
- The settings should be saved in profile 0 (the default reset profile).

Test procedures have been developed to verify the Communication Performance specifications listed above. These tests should be conducted on each pair of modem types anticipated to be used to communicate with the TTMS sites. In other words, if a new DC modem is to be used in a TTMS site, it should be tested with all the modem types used in the data collection center to ensure compatibility and performance. If the data collection modem is to be replaced with a new type of modem, the new modem should be tested with as many DC modems used in the field as is practical.

The final report for this task is included in Appendix B.

4. Telephone Line Surge Suppression

Summary of Objectives

Lightning is a significant problem for the over 300 Telemetered Traffic Monitoring Sites (TTMSs) currently in use by the Florida Department of Transportation (FDOT). Surges generated by the lightning can enter the TTMS equipment through any one of the wires entering the equipment cabinet. Telephone lines are particularly vulnerable to lightning surges due to their long lengths offering greater opportunity for induced or direct strike surges. Historically, the FDOT has used surge suppressors to mitigate all but the most severe surges from damaging the modem and other equipment in the TTMS cabinet. These surge suppressors have been successful at protecting the equipment, but the suppressors have often been damaged or destroyed by these surges. Replacing the surge suppressors is expensive, especially in terms of manpower, and the TTMS data cannot be collected until the suppressor has been replaced.

The goal of this task was to determine the appropriate specifications and test procedures for identifying surge suppressors that will protect the equipment in the TTMS cabinets from telephone line surges, and will be resilient to surge suppressor failures.

Activities Conducted

The initial phase of this task was analysis and testing to determine the telephone line surge environment experienced by the TTMS sites. Failed surge suppressors were examined and tested to determine the mode of failure. It was discovered that the older suppressors were basically fuses that blew when exposed to high currents to protect the equipment. This was effective protection, but resulted in significant suppressor failures and expensive replacement costs. Newer suppressors used were based on gas tubes that allowed the surge currents to arc across a small gap and be dissipated to ground. These suppressors rarely failed, and when they did it was often due to causes other than surges (e.g. ants in the suppressors). Only a few of the suppressors had the physical damage expected from the apparently rare direct lightning strike.

To further quantify the lightning surge environment, hand-held data logging meters were installed in a few TTMS sites. These meters were able to log the time and peak voltage of surges entering through the telephone lines. The results from these tests demonstrated that some TTMS sites are experiencing a large number of surges. One particular site averaged 48 surges per day over the length of the test. The results from these field tests and the analysis of the failed suppressors indicated that the suppressors were not typically experiencing excessively large surges such as a direct lightning strike. The conclusion is that the surge suppressors for telephone lines need to be able to withstand large numbers (>1000) of significant surges (1000's of amps) while clamping the maximum voltage output to the modems to the range of 200-300 volts. This clamping voltage range is above the telephone ring voltages normally found on a telephone line and low enough to be reasonably certain that the surges will not damage the modems.

The second phase of the effort was to test existing surge suppressors using a surge generator. The goals from these tests were to determine the resistance of the suppressors to failure, to develop specifications for future telephone line surge suppressors, and to develop test procedures to validate the specifications. A surge generator was acquired for these tests with the capability to generate current surges up to 6000 Amps (IEEE standard 8/20 μsecond surges). Testing was performed on surge suppressors acquired or borrowed from EDCO, Citel and Surge Suppression, Inc. Also, a surge protector designed specifically for the FDOT by Thomlinson Instruments and Controls, Inc. was tested. The EDCO and Citel suppressors used gas tubes as their primary means of dissipate the surge currents. The designs of the Surge Suppression devices were proprietary, but the specifications referred to metal-oxide varistors (MOVs) as the primary elements of the devices. The Thomlinson surge protector was based on MOVs and a choke coil (inductor).

Each of the surge suppressors were subjected to a single current surge of magnitude 6000 Amps without complete failure. Measurements of the output waveforms indicated that the output voltages of the gas tube-based devices shunted the output voltage to below 100 Volts by about 10 microseconds (μsec). The MOV-based Surge Suppression devices required about 30 μsec to shunt the voltage to below 100 Volts. Also, the output voltage waveform varied as the number of surges increased (not an unexpected result for MOVs), but the changes would not likely affect the protection offered by the devices. The Thomlinson surge suppressor required over 40 μsec to shunt the voltage below 100 Volts, but it was the only suppressor that eliminated the initial high-voltage spike on the output of the suppressor. The peak voltage output recorded on the output of the Thomlinson surge suppressor was less than 200 Volts.

Endurance tests were conducted on each type of telephone line surge suppressor. A total of at least 10,000 surges of 6000 Amps were attempted on each suppressor. The EDCO suppressor and the Surge Suppression S-D140-2X showed no deterioration during the tests. The output voltage waveform did not vary significantly and no physical damage was observed. Both Citel surge suppressors suffered some damage during testing. The damage was limited to connections at the suppressor inputs underlining the need for solid connections on the suppressors. The Surge Suppression S-TC-2 telephone line suppressor failed in less than 1,500 surges with obvious damage to the underlying components. The Thomlinson surge suppressor failed between 3000 and 4000 surges when one of the MOVs was physically destroyed.

Results and Conclusions

From the tests undertaken, it is apparent that a gas tube-based surge suppressors offer the best protection and are among the most reliable of the available surge suppressors. From the environmental tests that were run, it was shown that it is not one big surge that is killing the surge suppressors, but a number of small ones. Therefore it is appropriate to acquire lower rate suppressors that can withstand a large number of surges that a higher rated one that is not resilient enough to withstand a large number of the small surges.

The following are the recommended telephone line surge suppressor specifications:

- Peak Surge Capability: minimum of 10,000 Amps
- Resiliency: 10,000 surges of magnitude 6,000 Amps (IEEE 8/20 μsec waveform)
- Maximum Operating Voltage: 150 – 200 Volts
- Clamping: Output Voltage clamped to below 200 Volts within 10 microseconds
- Potting: The electronics contained in the surge suppressor should be potted, sealed in epoxy or otherwise sealed.
- Connectors: Telephone Line Side: Solid mechanical connectors such as spade lugs with washers.
  Modem Side: RJ-11 modular telephone line jack and minimum 5' RJ-11 cable for connecting to the modem.

Specifications #1 and 3 can be met by the ratings of the suppressors. Tests were developed to determine if the suppressors meet the resiliency requirements of Specification #2. Specification #4 can be verified by capturing the voltage waveform on a storage oscilloscope during the resiliency testing.

The complete final report for this task is included in Appendix C.

5. Evaluation of Bonding Materials Used in Piezoelectric Axle Sensor Installation

Summary of Objectives

The main goal of this research project was to develop test procedures that can be used to test adhesives for installation of piezoelectric axle sensors in the State of Florida. In addition, this research undertaking was also aimed at developing material specifications that will be used to select adhesives to achieve long-term field performance of piezoelectric axle sensors. The study was prompted by the fact that there are no standard procedures locally and nationally for testing adhesives and no state has so far developed material specifications for adhesives specifically for use in piezoelectric sensor installation.

Long-term observation of sensor performance in Florida suggested that the use of adhesives with characteristics unsuitable for Florida traffic, pavement, and environmental conditions might be contributing to premature failures of piezoelectric sensors. The excessive failures of piezos at telemetered traffic monitoring sites (TTMS) is of major concern to the Florida Department of Transportation (FDOT) because of the high cost of replacements and the attendant disruption of traffic flow. This summary gives an overview of adhesives approved for use in Florida, the methodology used in the study, findings, and recommendations.

Activities Conducted

Information supplied by the Project Manager, Mulder Brown, indicated that there are five adhesives that have been approved for use in the State of Florida. These adhesives are G100 by E-Bond Epoxies, 7084 by Dynatron/Bondo Corporation, P5G by Electric Control Measurements, AS475 by International Road Dynamics Inc., and PU200 by Global Resins Limited.

G100 by E-Bond Epoxies: G100 is an epoxy-based material that has invariably been used in Florida for approximately 18 years for piezo installation and other purposes such as patching and placement of anchor bolts, dowels and pins in concrete surfaces.

7084 by Dynatron/Bondo Corporation: This is also an epoxy-based adhesive that is supplied in two parts—resin and hardener.

ECM P5G by Electronic Control Measurement: This is an acrylic-based adhesive supplied in two parts—resin and hardener. The hardener is peroxide. ECM P5G is also mixed with fine filler material intended to improve bonding. The filler material commonly used is dry sand.

AS475 by International Road Dynamics (IRD) Inc.: This adhesive is also acrylic-based and supplied in two parts—resin and hardener. The hardener is composed of benzyl peroxide organic (PBO) powder. The resin is supplied already pre-mixed with fine filler material that, according to the manufacturer, provides strength and consistency to the adhesive mixture. The filler material is made of fine aggregate and prevents the resin from cracking by serving as a heat sink for the significant heat created during the curing of the resin.

PU200 by Global Resins Limited: This is a polyurethane-based adhesive that is also supplied in two parts consisting of resin and hardener. In addition, the adhesive is supplied in two versions—one for winter installation when outside temperature is below 40^{o}F and another for summer installations when outside temperature is above 40^{o}F.

A research protocol was designed to evaluate the performance of piezos so as to recommend which adhesives would be suitable for Florida conditions. The protocol included (a) comprehensive literature search on the characteristics of epoxies, acrylics, and polyurethanes, (b) survey of the experience of State Departments of Transportation in the U.S. on the use of these adhesives for piezo installations, (c) laboratory testing of the approved adhesives, and (d) long-term field monitoring of ANOVA-designed experiments.

The materials studied can be categorized in three main groups—epoxies, polyurethanes, and acrylics. Different sources that were used to examine each type of bonding materials i.e., literature review, state experience survey and laboratory testing suggest that there are distinctive properties associated with each material. The following discussion is a synthesis of information found from various sources and would build a basis for the recommendations about to be made.

Epoxies**:** The laboratory results shows that epoxies are associated with hardness behavior, high compressive strength, with high modulus of elasticity. No significant difference was observed between epoxies and other types of materials. The epoxies were also found to have relatively higher peel strength with an exception of Bondo 7084. The epoxies also resulted with higher peel strength. However laboratory results suggested little flexibility of epoxy materials with exception on E-Bond 1261. The state survey respondents commented on some epoxies. The respondent from the State of Connecticut reported that G100 performed well in concrete pavement installations while it developed cracks when sensors were installed in asphalt pavements. The State of Utah reported that it had used G100 in the past but it failed in the first summer after installation. The State of West Virginia also reported that at numerous sites installed with G100 cracks were observed. The State of Nebraska reported that 7084 adhesive was very stiff during installation but had minimum cupping and weather effects. The State of Kentucky reported that 7084 adhesive did not have good long term bonding characteristics. E-Bond 1261 was not in use around the country at the time of this study, therefore there was no information about the product from states' survey.

Polyurethanes: As with epoxies, the laboratory results showed that polyurethanes are associated with hardness behavior but with lower compression strength and modulus of elasticity. The results further suggest that polyurethanes have the lowest peel strength among the rest of the materials. PU200 is the only polyurethane material that was reported to be used by some states. The respondent from the State of Virginia said that PU200 has not performed well in the state and he suspected that the material could be suffering from long-term creep and stress relaxation problems. In addition, according to one FDOT contractor, eighteen sites in Ohio installed with PU 200 have failed. The contractor suspects that part of the problem with PU200 is excessive shrinkage, which affects bonding between the sensor and the adhesive.

Acrylics: Contrary to epoxies and polyurethanes, laboratory test results suggested that acrylics are softer than epoxies and polyurethanes. The laboratory results also indicated that acrylics have lower compressive strength, lower modulus of elasticity and moderate strain hence reasonably more flexible than epoxies and polyurethanes, with an exception of E-Bond 1261. While P5G and P6G resulted in relatively lower peel strength, AS475 resulted in higher peel strength than some polyurethanes and epoxies. Several states reported on performance of acrylics (P5G and AS475). The State of Kentucky reported that P5G had good long term bonding characteristics while Colorado surmised that since switching to P5G from other adhesives, the failure rate of piezo installations has been greatly reduced. The State of Montana reported that they have been pleased with the performance of P5G since most of the failures have been in cabling, sensor itself, and pavement, but generally not the adhesive. However, Montana also reported that they noticed that when P5G is installed in pavements with thin overlays it generally tends to fail prematurely. The State of Washington reported that using AS475 has greatly reduced their piezo installations failure rate. Likewise, the State of Utah reported that the field crew prefers AS475 over PU200 since it mixes and pours well, as well as it cures quicker than PU200. The study by Euber *et al*. (1994) also found that acrylic-based adhesives performed better than epoxies in most cases during the field trials.

Results and Conclusions

The preliminary recommendations on the type of adhesives to be used in Florida are based on the review of literature, contact with various state personnel and technicians, survey of different states' practices, review of manufacturer's own technical data sheets, and the laboratory test results. The recommendations are termed preliminary since long-term performance monitoring of the recommended grouts in the field is needed to ascertain their suitability for Florida environmental and traffic conditions. A prolonged field monitoring will also lead to recommendation of test procedures and material specifications to be used in approving future adhesives submitted by manufacturers for review by FDOT. These recommendations are related to adhesives used only in installation of sensors in asphalt concrete pavements.

The research results summarized above indicate that acrylic-based adhesives generally have better performance characteristics compared to epoxy and polyurethane-based adhesives. Acrylics tend to have characteristics similar to flexible pavements, i.e., good impact resistance and flexibility. In addition, the research results indicated that acrylics also have reasonable peel and shear strength. Likewise, numerous states that have used adhesives extensively report a reasonable degree of satisfaction with the performance of acrylic-based adhesives in flexible pavements.

The difference in performance of acrylics compared to epoxies and polyurethanes can also be explained by considering the glass transition temperature of these materials. Increased stiffness at low temperature may result in cohesive failure of the adhesive. At very low temperatures, the adhesives become very rigid. The rigidity is represented by a high modulus of elasticity. After reaching the glass transition temperature, T_g, the increase in temperature results into a rapid decrease in modulus of elasticity. Eventually, a point is reached beyond which the modulus of elasticity remains relatively constant as the temperature increases (rubbery region). A good adhesive material for application with flexible pavements should have a low glass transition temperature, T_g. The brittleness and rigidity of epoxy and polyurethane-based adhesives suggest that they do have a high glass transition temperature and thus they become more brittle than acrylics at temperatures between T_g and T_{room}. This phenomenon might partially explain lack of good bonding characteristics of epoxies and polyurethane adhesives used in colder regions of the United States.

Based on the literature review, state survey and laboratory test results it is recommended that the Florida Department of Transportation should use acrylic-based adhesives with increasing frequency in the installation of piezoelectric axle sensors in asphalt concrete pavements. Though there are only two acrylic-based adhesives currently approved by FDOT, i.e., IRD AS475 and ECM P5G, it is recommended that P6G, the modified product of P6G be included in the Florida Department of Transportation approved list of adhesives. It is also recommended that a monitored field test be conducted on E-Bond 1261, the only epoxy-based material that had a number of properties that may be suitable for installation of piezoelectric axle sensors in asphalt concrete pavements.

The complete final report for this task is included in Appendix D.

6. Mining of Florida ITS Data for Transportation Planning

Summary of Objectives

The Florida Department of Transportation has been actively involved in implementing Intelligent Transportation Systems (ITS) strategies to improve safety and efficiency of travel in urban transportation networks. Consequently, several Advanced Traffic Management Systems (ATMS) have been created for the purposes of monitoring and managing traffic on freeways through real time and area wide surveillance that facilitate rapid incident detection and clearance.

The sensors used for freeway surveillance include inductive loop detectors and non-intrusive detection systems such as video imaging detection (VID). The FDOT Transportation Statistics Office, which is responsible for collecting and disseminating traffic data realized the potential of mining the ITS data to augment data collected by temporary and permanent count stations distributed throughout the Florida highway system.

The major objective of this project is to determine the efficacy of using ITS data for transportation planning purposes. The Transportation Planning Statistics Office recently commissioned a pilot project study on site 750196 at station 36 on I-4 corridor in Orlando. The study was able to convert ITS data at this station through a simple Oracle SQL-based computer routine. The data was converted from minute averages of volume and speed to hourly summaries of volumes and speeds for each lane in both directions at this site. Thus, the objective of this study is to build upon the positive results of this pilot project and to develop a mechanism that can be used statewide to capture and convert ITS data into a format compatible with that of TTMS and temporary count sites.

Activities Conducted

<u>Activity 1: Review literature</u>

A comprehensive literature search of both published and unpublished information was conducted to determine similar efforts in other states and other countries. Numerous ATMS systems have been established in recent years around the country, generating a multitude of traffic data. The information on similar efforts was solicited through search of library documents and databases and through surveys of transportation professionals. The results from this effort were documented and used in other tasks.

<u>Activity 2: Studying the Orlando Network Configuration</u>

The network at the Orlando Regional Traffic Management Center (RTMC) has a number of computers on one domain called FDOT_D5MIS. The network has two servers that are labeled COMServer and MISServer. The COMServer is used to gather data from 90 detector stations installed in the field. The data are stored in a text file called detector.dat—which is in the directory c:\programfiles\pb_fi…\I-4a\detectordd\b238\. The b238 directory is shared as b238 on COMServer share name for all users of FDOT_D5MIS domain. The FDOT_D5MIS domain can be accessed using the proper username and password. The data in the detector.dat file is in a format shown below:

<Hour:Minutes:Seconds- B238I4DD: 5<ITS Station Number><Lane Number>, , <Speed>, ,<Volume>, <Occupancy>.

Hours – 0 to 23
Minutes – 0 to 59
Seconds - 0 to 59
ITS station numbers – 2 Digit Numbers
Lane Numbers – 01, 03, 05, 11, 13, 15
Speed – 2 digit number
Volume – Extrapolated value for the number of vehicles passing per hour.
Occupancy – Not know

```
00:00:01- B238I4DD:  55401,P, ,  0,Y, 120,  0.0,
00:00:01- B238I4DD:  55403,P, , 63, , 840,  5.0,
00:00:01- B238I4DD:  55405,P, , 58, , 600,  3.0,
00:00:01- B238I4DD:  55411,P, , 61, , 600,  4.0,
```

THE MISServer acts like a web server. A program in the server converts the streaming video input to jpeg images. These images are later uploaded on to a central location. Both COMServer and MISServer run on Windows NT network. Because of concerns for security, the network at the RTMC is not linked to any other network. In addition, none of the computers in the network is connected to the Internet. The only way to connect to either of the servers from a remote location is through a dialup server called SHIVA, which has number of dedicated phone lines assigned to it.

The University of Central Florida (UCF) has a computer resident in the RTMC control room and connected to the network through one hub. The UCF computer downloads the detector log file and video images through a computer program written to capture the data. The UCF computer program runs on Windows 2000 server platform and it captures the data every 60 seconds throughout the day. The data captured by this computer are then transmitted to a UCF laboratory using a dedicated T1 line.

<u>Activity 3: Installing a Computer in Orlando</u>

To capture the detector log file for mining of the ITS data, a computer had to be installed in the FDOT_D5MIS domain. A workgroup had to be created to accommodate the computer. One can log into the computer using the proper username and password. The computer, which runs on Windows 2000 server platform, is on a workgroup called FAMU_FSU_WORK. The F drive of this computer is mapped to the detector.dat file in the COMServer's b238 directory which has the information needed for this project. The FAMU-FSU computer was configured to use the same gateway as RTMC network and was given an IP address from the pool RTMC allocated for this purpose.

The computer is configured to run as a dialup server using a network card connected to the local Ethernet, which allows it to access the RTMC COMServer. The computer has a modem that can be used to dial up to upload or download files using a dedicated telephone number. Software called PCAnywhere was installed on this computer. A modem host is always running on the computer to accept incoming connections, and access is protected using a username and password. PCAnywhere should be installed on client to enable the transfer of data. The FAMU-FSU computer acts as host to any incoming connections. PCAnywhere client—which might be any outside computer—dials into the server to establish a remote interface. After the connection is established files can be downloaded from the host computer, i.e., FAMU-FSU.

Activity 4: Internal Data Capture

A driver program was written to poll the detector log file located in the COMServer. The driver on COMServer polls the detector stations at regular intervals of 30 seconds and writes the polled detector data into a detector.dat file on COMServer. The detector.dat file is written at regular intervals of 30 seconds. The data amounts to 350 MB of information, which has to be transferred to FAMU-FSU computer using the Ethernet (T1 line). The way COMServer refreshes the detector log file is not fixed thus creating redundant data that need to be purged from the new file. To solve this problem, the driver program reads the detector.dat file constantly and ignores the data that have already been collected. Only new data are collected using the time stamps on every detector entry. All the new data collected is stored in hourly files. This is done in order to reduce large file sizes and also reduce the chances of loosing data in case of system crash. The major problems faced in capturing the detector data include the amount of the data and the refresh time of the data. The total data collected for the day amounts to 90 MB.

A computer program was written and installed on the FAMU-FSU computer to gather the data from the detector log file. The program file name is ReaderByChar.java and was written in Java programming language. For each detector station, the program creates a file for it and writes the data into the file every hour. The detector files are located in c:\detectoroutputfiles directory and have the data for all detectors installed in the field. These file are given names in the format YYYY-MM-DD-HH.dat in which YYYY=year, MM=month, HH=hour. Thus, at the end of the day there will be 24 files for each detector station.

Results and Conclusions

The outcome of this pilot project has shown that it is possible to extract planning-compatible traffic data from loops installed on freeways for incident surveillance and other ITS purposes. The FDOT District V Planning Office is currently able to download traffic data composed of hourly volumes from several sites along the Interstate 4 corridor. With the help of the District V ITS Office, Mr. Jerry Traudt is currently able to access the data through the local area network instead of telephone line connection. This has greatly increased the data accessibility and ease of download of daily log files.

Because of this effort of this project, it was expected that the Florida Department of Transportation would potentially save $200,000 by foregoing the installation of new loops for collecting planning data in areas that ATMS loops already exist on I-4. With the expansion of ITS activities along Interstate 4 corridor, additional sites will be incorporated thus reducing the need to install TTMS sites along the corridor leading to additional savings.

For the next phase of the project, a Consultant has been chosen to develop data mining programs and protocols for capturing data from all existing and future ATMS centers in Florida. The Consultant will also integrate data mining programs into the Data Warehousing project that is currently ongoing and which is aimed at streamlining the collection, management, and interoperability of Florida transportation data.

A report on this task has been completed and transmitted to the FDOT Transportation Statistics Office. The report contains sensitive information concerning login usernames and passwords. Therefore, the task report is not included.

7. Conclusions

This project has included several efforts to support and improve the operation of the FDOT Telemetered Traffic Monitoring Systems. The major areas of support included:

1. Communications
2. Lightning Surge Protection
3. Bonding Material for Piezoelectric Axle Sensors
4. ITS Data Mining

The results of the efforts in communications include recommendations for installation of cellular communication to TTMSs, and draft specifications for the acquisition of modems. The work on site 9936 revealed that the installation, particularly that of the antenna, has a significant impact on the performance of the communication with the site. Also, attention must be given to the selection of the cellular provider, especially in remote locations where few cellular towers are located. The modem performance study resulted in specifications concerning modem protocols and performance. The results indicated that the newer 56K modems do not perform as well as slower modems for data transfer applications. Also, the modem initialization strings from some of the TTMS equipment vendors are unnecessarily complex. These strings should be reviewed carefully to eliminate repetition of defaults, invalid commands and contradicting instructions.

The lightning surge protection efforts provided recommended specifications for telephone line surge suppressor. Initial field experimentation revealed that the TTMS telephone lines were subject to a large number of surges from passing thunderstorms. Therefore, a large number of the failed surge suppressors were due to the repetition of surges rather than the relatively rare direct lightning strike. Therefore, it was recommended that future surge suppressors acquired be resilient to large numbers of surges. The surge generator purchased for this effort can be used to test potential vendor products to determine their protection of the modems and their resilience to multiple surges. It is recommended that this research effort be extended to include the design of improved surge protectors, and the assessment of low-voltage surge protectors for in-pavement sensors.

Bonding materials for piezoelectric axle sensors were investigated and tested to determine the best material for in-pavement installations. The types of bonding materials assessed included epoxies, polyurethanes, and acrylics. The results of surveys, literature reviews, reviews of data sheets and laboratory tests concluded that acrylic-based adhesives have better performance. It is also recommended that long-term performance studies be conducted.

The ITS data mining effort concluded that it is feasible to extract planning compatible traffic data from loops installed on freeways for incident surveillance and other ITS purposes. The FDOT is now capable of extracting traffic data composed of hourly volumes from several sites along the Interstate 4 corridor through a local area network. Using the ITS data will potentially save $200,000 by foregoing the installation of new loops for collecting planning data in areas that ATMS loops already exist on I-4.

Appendix A
Draft Text of *Research Today* Article in Winter 2001

Author: J. Darryll Dockstader, Technology Transfer Manager, Research Center, Florida Dept of Transportation, (850) 414-4613.

On April 30, 2000, work began on **Contract #BC-596**, *Improving the Operation of FDOT Telemetered Traffic Monitoring Sites*. At the time, the Department monitored 6,987 traffic count sites, including 310 permanent Telemetered Traffic Monitoring Sites (TTMSs), most of which utilized wired modems. The primary objective of the study was to develop specifications and compliance tests for material and equipment to be used at TTMSs, focusing particularly on communication modems and in-pavement sensor materials used for installation.

The Florida Department of Transportation (FDOT), however, had been encountering difficulties with a remote site (9936) located on I-10 and within the Osceola National Forest. Co-sponsored by the Federal Highway Administration (FHWA), site 9936 was designed to provide data to test the effectiveness of the Superpave mix. As such, it is a weigh-in-motion (WIM) site that daily collects over 300 kilobytes of information and, as a remote site, is designed to utilize cellular technology to transmit that data.

Establishing reliable cellular communication with the site, however, proved problematic. The antenna was set, in close proximity to a power conduit and lightning rod, upon a concrete column beside the highway. Alternate antennas were tried. Antenna location was changed, so that to increase its height the antenna was placed on a utility pole located on the edge of the overpass. Low-loss cable was utilized and modem string modifications were made.

However, FDOT was still unable to automatically retrieve the data because of unreliable connections. In order to provide project information to the FHWA on a monthly basis, Department personnel had to conduct weekly on-site downloads to gather data (on-site hardware can store approximately a week's worth of data). FDOT was committed to the cooperative Superpave study, but unsatisfied with the labor intensive means of data collection.

Project BC-596 provided an opportunity to conduct a study within a study, to investigate why cellular communications failures were occurring at site 9936. Dr. Bruce Harvey, Assistant Professor at the FAMU-FSU College of Engineering and Principal Investigator of the study, systematically tested the site's communications system, taking three primary steps: (1) researching cellular coverage in the area, (2) verifying cellular equipment at the site, and (3) conducting on-site testing with the assistance of a local cellular technician.

Dr. Harvey found that the nearest station of FDOT's cellular provider, located approximately 11 miles from site 9936, had a service radius of 10.9 miles. Another cellular provider, also with a 10.9 mile service area radius, was located approximately 8 miles from the site. The equipment at the site was good but not set up to maximize reception. High reflections interfered with signal reception, and mechanical inspection revealed that the antenna feed had been moved.

Based upon Dr. Harvey's findings, FDOT changed its cellular provider to the host with the closer tower and replaced the antenna, which was then adjusted horizontally to point slightly away from the station. The highest signal level (-78 to -75 dBm) occurred when the antenna pointed just to the side of the trees that had been obstructing the line-of-site to the cellular tower.

Other important lessons learned, including those resulting from the earlier remedial attempts made by FDOT, were (1) selecting low-loss cable for long runs (greater than 20 feet), (2) being wary of using multiple cable adaptors, (3) mounting antennas away from metal and other dense objects, (4) allowing only RF engineers to adjust antennas, (5) using directional antennas when needed, and (6) not relying on signal level indicators on cellular phones, as they may not indicate the proper provider.

For more information on this project, contact Harshad Desai at (850) 414-4718, harshad.desai@dot.state.fl.us

Appendix B
Modem Performance Study Report

This appendix includes the full report submitted to the FDOT Transportation Statistics Office for the modem performance effort.

Interim Technical Report

Modem Performance Study

PROJECT:
Improving Operation of FDOT Telemetered Traffic Monitoring Sites
(FDOT Contract No. BC-596, FSU Project No. 613054139)

Submitted by:

FAMU-FSU College of Engineering
2525 Pottdamer Street
Tallahassee, FL 32310-6046

Principal Investigator:

Bruce A. Harvey, Ph. D., Assistant Professor
Department of Electrical and Computer Engineering
Phone: (850) 410-6451
Fax: (850) 410-6479
Email: bharvey@eng.fsu.edu

EXECUTIVE SUMMARY

Telephone line modems are the main vehicle used to collect traffic data from the over 300 Telemetered Traffic Monitoring Sites (TTMSs) currently in use by the Florida Department of Transportation (FDOT). Most of the TTMSs sole source of power is 12 Volt solar panels and thus the modems used in the field must operate on 12 Volts DC and draw very little power. Historically it has been observed that some of the DC modems used in the TTMSs and some of the standard desktop modems used for data collection do not perform as well as is expected. Typical problems include inability to communicate, slow connection speeds, frequent drop of signals and data errors during transmission.

The FDOT tasked the Electrical and Computer Engineering Department of the Florida A&M University-Florida State University (FAMU-FSU) College of Engineering with the task of determining the causes for the poor performances and the apparent incompatibilities between certain modems. In addition, the task called for the development of specifications and validation test procedures to mitigate the performance and incompatibility problems in future modems. Dr. Bruce A. Harvey directed the research efforts and divided the effort into three primary tasks: (1) Conduct a survey of available DC modems including specifications, communication protocols supported and manufacturer's chipset; (2) Acquire a sample of modems (DC and desktop) and a telephone line emulator, and conduct performance tests on the modems to quantify performance differences between modems for the purpose of defining specifications for future modem purchases; and (3) Examine the modem strings defined by the traffic monitoring equipment manufacturers for use on particular modems.

The survey of DC modems identified modems ranging in top speed of 33,600 down to 2,400 bits per second (bps). Most could operated on 12 Volts DC though some could operate on as little as 5 or 9 Volts DC. A couple of modems had sleep modes allowing lower power requirements. A couple of modems had specialty protocols for handling wireless (cellular) links including MNP 10 and MNP 10EC, however, cellular-specific modems were not directly addressed in this study. All of the DC modems found operated using either the Covenant (formerly Rockwell) chipset or the Motorola chipset. Desktop modems were found using Covenant, Lucent and US Robotics chipsets. The specifications for the modems indicated that any pair of the modems found should be able to operate together across a telephone line. The handshaking protocols allow the modems to negotiate the best protocols available in both modems.

A Teltone TLE-A01 telephone line emulator was acquired to test the compatibility and performance of various pairs of modems. A total of eight (8) DC modem types and four (4) desktop modem types were acquired for testing in this phase of the project. Using the TLE-A01, pairs of modems were evaluated in the presence of ideal line conditions, signal attenuation, noise and combinations of impairments. Under ideal line conditions it was found that all pairs of modems could successfully negotiate parameters and transfer data; thus the modems were all essentially "compatible." During noise impairment tests, most modem pairs were able to connect and communicate with added noise levels up to 55 to

60 dBrn (-35 to -30 dBm). Most modem pairs with more susceptibility to noise included desktop modems with top speeds of 56 kbps; this is likely due to optimization of the modems for Internet dialup speeds. Telephone line attenuation test demonstrated that all modems operated with line attenuations up to 24 – 34 dB. Unlike the noise tests, there was no strong correlation between modem maximum speeds maximum line attenuation. Modem pairs that operate consistently with attenuations of 30 dB or more will likely operate well in the field. Combination of impairment tests confirmed that 56K modems are more sensitive to noise when communicating with 14,400 or lower speed modems.

Modem strings used to specify the operating parameters of the data collection modems have been a particularly vexing problem for the FDOT. Generally, the manufacturer of the traffic monitoring equipment specifies the modem strings for each modem type. Investigations of the modem strings currently in use found them to be overly complex. Often the strings repeated almost universal modem default conditions, and enabled or disabled features that were overridden by other commands.

The results of the analysis and testing performed included a number of recommended specifications. These recommendations are as follows:

Protocols and Operating Speeds:

- Modems speed: 14.4K (V.32bis), 28.8K (V.34) or 33.6K (V.34bis).
- Generally 56K modems should be avoided.
- DC modems should operate at their highest available speeds.

Communication Performance:

- Each modem purchased must be able to connect with equal (same in both directions) white noise levels of at least 55 dBrn (-35 dBm).
- Each modem purchased must be able to connect and operate with equal attenuation levels of at least 28 dB.
- These specifications must be met when communicating with data collection modems used at the FDOT.

Data Compression and Specialized Protocols:

- V.42bis has better compression ratios than MNP 5 and should be preferred.
- MNP 10, MNP 10EC and MNP 10ETC are protocols specifically designed for cellular communication. These are not standards however and have limited usefulness for wired modems. Thus they should be generally avoided or disabled.

Initialization Strings:

- Modems should be reset to factory defaults before configuration. (It is recommended to store in profile 0 as well.)
- Modems at the TTMS locations need to be configured to answer the phone when it rings (e.g. ‘ATS0=1’).

- Systems that transfer binary files need to ensure that software flow control is disabled; this is default in all modems tested.
- Special functions such as power saving or cellular protocols need to be enabled.
- Repeating factory defaults in the modem string should be avoided to reduce errors.
- The settings should be saved in profile 0 (the default reset profile).

Test procedures have been developed to verify the Communication Performance specifications listed above. These tests should be conducted on each pair of modem types anticipated to be used to communicate with the TTMS sites. In other words, if a new DC modem is to be used in a TTMS site, it should be tested with all the modem types used in the data collection center to ensure compatibility and performance. If the data collection modem is to be replaced with a new type of modem, the new modem should be tested with as many DC modems used in the field as is practical.

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1. INTRODUCTION

The purpose of this study was to evaluate the performance and characteristics of telephone line modems, and to develop specifications or recommendations for the future purchase of modems for use in telemetered traffic monitoring sites (TTMSs). Data is collected from remote TTMS units using telephone modems. Many of the TTMS sites rely exclusively of 12 Volt DC power from solar panels, and thus the modems used in these sites are low-power DC modems. Historically it has been observed that some of the DC modems used in the TTMSs and some of the standard desktop modems used for data collection do not perform as well as is expected. Typical problems include inability to communicate, slow connection speeds, frequent drop of signals and data errors during transmission.

The causes of the modem problems have not been fully identified. Most of the TTMS modems communicate via standard telephone lines with very good voice quality (all that is guaranteed by the local telephone companies). A few TTMS sites use cellular phone service with a unique set of problems not addressed by this study. There is a variety of DC modems operating at the TTMS sites operating at different speeds, built on different modem chipsets, and of varying ages. Some of these modems seem to perform better or more reliably than do other modems. Therefore, the primary objective of this study is to provide specifications, standards, tests or information that will aid the FDOT in selecting future modems for use in TTMS sites that will perform satisfactorily and reliably.

A number of tasks were performed in order to develop the specifications for future modem purchases. First, the modems available in the market were surveyed, and information including communication protocols, chipset manufacturers and power requirements was collected. Next, a sample of modems and a telephone line emulator were acquired to perform performance tests on the modems. Following these tests, an analysis of the modem strings used by the modems (typically recommended by the data collection equipment manufacturers) was performed.

2. MODEM SURVEY

A modem survey was conducted to accomplish a number of goals. First, was to determine the number and variety of DC modems available to the FDOT. Secondly, the survey was conducted to identify the actual number and manufacturer of modem chipsets in the modems. Finally, the power requirements of the various DC modems were recorded.

The primary data collected for each modem included available communication protocols (affects speed, data compression, etc. of the modems), manufacturer of modem's chipsets, and power requirements of the modem. The information collected has been summarized in Table 1. The modems highlighted in Table 1 were the ones selected for testing in the next phase of this project. Research on the various chipsets and modulation protocols was also conducted and the results were summarized in Appendix A.

Table 1. Summary of Modem Protocols and Power Requirements

DC MODEM	TYPE	RATE (bps)	PROT0COLS	PWR SUPPLY	Vdc	CURRENT	MANUFACTURER
DLM 4100 ET		9600	A,B,C,D	12V/24V	12	300 mA	Arc Electronics
IM-24LV	Cellular	2400	A,B,C,D,E,G	10V-36V	12	100 mA	Arc Electronics
IM-14.4LV	Cellular	14400	A,B,C,D,E,G,I,J	10V-36V	12	140 mA	Arc Electronics
IM-33.6LV	Cellular	33600	A,B,C,D,E,G,I,J	10V-36V	12	140 mA	Arc Electronics
Starcomm	Cellular	9600	A,B,C,D,E,I,J,K,N	9V-18V	12	600 mA	Starcomm
OEM CM900	Cellular	9600	A,B,C,D,I,J,K,M,N		5	800 mA	Arc Electronics
MIU 2.4LV	Dial up	2400	A,B,C	9V-36V	12	65 mA	Telenetics/ A.E.
Motorola V.3600	Dial up/ L.L.	33600	A,B,C,D,E,F,G,I,J,K	12V-60V			Telenetics/ A.E.
Ind. Modem 288	Dial up/ L.L.	28800	A,B,C,D,E,F,I,J,K	12V/24V	12		Arc Electronics
3342L	Dial up/ L.L.	33600	A,B,C,D,E,G,I,J,K,N	5.5V-14V	12	260 mA	Star Comm/ A.E.
MIU 9.6LV	Dial up/ L.L.	9600	A,B,C,I,J,K,M	9V-36V	12	115 mA	Telenetics/ A.E.
MIU 14.4LV	Dial up/ L.L.	14400	A,B,C,D,E,I,J,K,M	9V-36V	12	160 mA	Telenetics/ A.E.
MIU 28.8LV	Dial up/ L.L.	28800	A,B,C,D,E,F,I,J,K,M	9V-36V	12	205 mA	Telenetics/ A.E.
1442L	Dial up/ L.L.	28800	A,B,C,D,E,I,J,K,N	5.5V-14V	12	260 mA	Star Comm/ A.E
V.3400	Dial up/ L.L.	28800	A,B,C,D,E,F	12V-60V	12		Motorola
DSP 9600	Leased Line	9600	D	10V-53V	12		Telenetics/ A.E.
cascade 14.4	Dial up	14400	A,B,C,D,E,I,J,K,M	5.5V-14V	6		Diamond
cascade 33.6	Dial up	33600	A,B,C,D,E,F,G,I,J,K,M	5.5V-14V	6		Diamond
Starcomm 14.4	Dial up	14400	A,B,C,D,E,I,J,K	9V	9		Arc Electronics
Starcomm 33.6	Dial up	33600	A,B,C,D,E,F,G,I,J,K	9V	9		Arc Electronics
Micro-Aide 33.6	Dial up	33600	A,B,C,D,E,F,G,I,J,K	5V-36V	12V	85 mA	Micro-Aide

Highlighted modems are tested during this project.

Modulation Protocols

A: BELL 103	0 – 300bps
B: BELL 212A	1200 bps
C: V.22bis	1200, 2400 bps
D: V.32	4800, 9600 bps
E: V.32bis	4800, 7200, 9600, 12000, 14400 bps
F: V.34	2400, 4800, 7200, 9600, 12000, 14400, 16800, 19200, 21600, 24000, 26400, 28800 bps
G: V.34bis	2400, 4800, 7200, 9600, 12000, 14400, 16800, 19200, 21600, 24000, 26400, 28800, 33600 bps
H: V.90	56K, ...

Data Compression and Cellular-Specific Protocols

I: V.42bis	SETS THE COMPRESSION RATIO AT 4:1
J: MNP 5	SETS THE COMPRESSION RATIO AT 2:1
K: V.42	ERROR CONTROL PROTOCOL (MNP1 - MNP4)
L: MNP 7	SETS THE COMPRESSION RATIO AT 3:1
M: MNP 10	OLDER SPECIAL FEATURED PROTOCOL FOR CELLULAR ENVIRONMENT
N: MNP 10EC	ENHANCED MNP 10 PROTOCOL

Note from the modulation protocols listed in Table 1 that each modem should be compatible with all modems of lower speed. The handshaking between modems under ideal conditions is designed to arrive at agreed modulation protocols. Also, the handshaking allows the modems to select the common compression and other special protocols enabled in the modems.

Most of the modems can operate at 12 Volts as used in the FDOT TTMS installations. Many of the modems also specify a power supply current requirement (CURRENT) at a particular operating voltage (Vdc). The Starcomm 14.4 and 33.6 modems specify a sleep current of 5 mA while the Micro-Aide modem has a standby current rating of 0.5 mA. The sleep/standby mode of these modems can be programmed into the modems through the modem string to reduce power consumption during extended periods of non-use.

3. MODEM PERFORMANCE TESTS

Several DC-powered and desktop (AC-powered) modems were acquired for testing. The objectives of these tests were to quantify performance differences between modems for the purpose of defining specifications for future modem purchases. Anecdotal evidence from the use of older modems seemed to indicate that modems performed best when communicating with other modems using the same chipsets or even other modems from the same manufacturer. These tests were designed to quantify the performance differences in a controlled environment to identify the parameters, characteristics or capabilities that differentiate a "good" modem from a modem that performs poorly. The modems tested were:

DC Modems:
- Starcomm Modem – 14.4 (Rockwell/Conexant Chipset)
- Starcomm Modem – 33.6 (Rockwell/Conexant Chipset)
- Cascade 14.4 Data Modem (Rockwell/Conexant Chipset)
- Cascade 33.6 Data Modem (Rockwell/Conexant Chipset)
- Motorola V.3600 Modem (Motorola Chipset)
- Telenetics MIU14.4-LV (Rockwell/Conexant Chipset)
- Micro-Aide LPM 14.4 (Rockwell/Conexant Chipset)
- Micro-Aide LPM 33.6 (Rockwell/Conexant Chipset)

Desktop (AC) Modems:
- Win Lucent Modem (Internal Laptop – Chipset Lucent)
- US Robotics 56k (Chipset US Robotics)
- Zoom 56K (Chipset Lucent 'Oscera')
- Best Data 56k (Rockwell/Conexant Chipset)

3.1. Modem Test Setup

The modem tests were developed using a telephone line emulator (TLE) and two computers as shown in Figure 1. The telephone line emulator selected was Teltone TLE-A-01. This TLE, under computer control, can be used to vary multiple line parameters including noise and attenuation on the telephone line to emulate line conditions experienced by the modems.

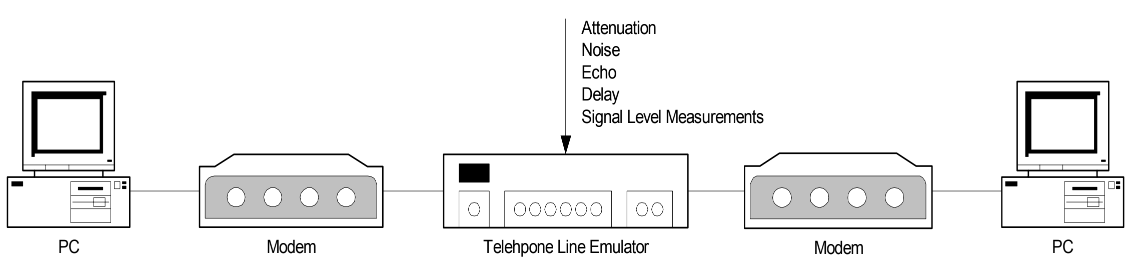


Figure 1. Modem Test Setup Block Diagram

The TLE-A01 (Teltone) unit's serial control cable was connected to the COM1 serial port on PC 1 (the leftmost computer in Figure 1). If connected to COM2 it would not be identified as connected and therefore the settings for local loop parameters, signal measurements, etc. would be default and could not be changed. The Teltone control software was installed on PC 1 from CD and an updated version was obtained from the website http://www.teltone.com. To change settings of the TLE parameters, go to start (from desktop), then to Programs and then to TLE PC to get the current settings.

The modems under test were connected to two of the phone line ports on the TLE using standard telephone extension cords (RJ45 connectors). The modems were then connected to the PC serial ports. On PC 1 the modem was connected to COM2; on PC2 the modem was connected to COM1 (except the internal laptop modem tested). The communications software used on both the computers was Procomm Plus 32. This software has variety of functions in it including the Bulletin Board Software (BBS) feature (not used in these tests).

Once the modems were connected as described above the modems can be used to communicate with each other just as any two modems connected to the public telephone system. The phone numbers for dialing are 3-digit numbers as indicated on the connectors on the front panel of the TLE. Note that the modem receiving a call must be set up to answer the phone call using the modem setup strings (typically “AT S0=1” is used to set the modem to answer on the first ring).

Details of the test set-up, and operation of the ProComm and TLE control software are provided in Appendix D.

3.2. Modem Test Plan

A test plan was designed including modem/chipset compatibility tests, and tests designed to analyze the robustness of the modems to the noisy and attenuated line conditions. The test plan was divided into 4 phases:

<u>Phase I. – Compatibility Tests, Ideal Line Conditions:</u>

Goal: To observe differences in performance of modems for different manufacturers and chipsets

In the first phase the compatibility and performance of modems were tested under ideal conditions i.e. under perfect line conditions. Modems with the following combinations were tested based on the availability of the combination and the requirements of the FDOT:

- Same chipset, manufacturer and protocols
- Same chipset and manufacturer but different protocols
- Same chipset and protocols but different manufacturer
- Same chipset but different manufacturer and protocols
- Different chipset and manufacturers but same protocols
- Different chipset, manufacturer and protocols

Note: When different protocols are mentioned it is implied that the modems may have compatible protocols but not exactly the same highest speed.

Phase II – Noisy Line Performance Tests

Goal: To test the compatibility & noise tolerance levels of modems using different combinations under noisy line conditions.

In this phase the communication line conditions for modems were made noisy to check the threshold level of modem performance under noisy conditions. The results were used to deduce which modems have better noise cancellation filtering along with compatibility with different modems. The combinations used are the same as in Phase I:

- Same chipset, manufacturer and protocols
- Same chipset and manufacturer but different protocols
- Same chipset and protocols but different manufacturer
- Same chipset but different manufacturer and protocols
- Different chipset and manufacturers but same protocols
- Different chipset, manufacturer and protocols

Phase III – Attenuated Line Tests

Goal: To vary the attenuation of the signal levels and evaluate the performance of modems under noise-less line conditions

In this phase of testing the ability of the modems to compensate for line attenuation was studied. The range of gain adjustment and the handshaking between modems to set the signal gains was also measured. The combinations used are the same as in Phase I:

- Same chipset, manufacturer and protocols
- Same chipset and manufacturer but different protocols
- Same chipset and protocols but different manufacturer
- Same chipset but different manufacturer and protocols
- Different chipset and manufacturers but same protocols
- Different chipset, manufacturer and protocols

Phase IV – Focused Tests, Combinations of Impairments

Goal: Based on the above tests results, some special tests were carried out to isolate and quantify performance of the modems under combinations of impairments and other issues related to phone line conditions.

The special tests included some advance testing based on the performance and compatibility results achieved in the previous phases. In this phase a table/list of different performance measures of different modems tested was also generated. The special tests were determined by the results from Phases I – III and were selected from the list below:

- Combination of parameters (e.g. noise and attenuation)
- Sidetone Signaling
- Ringing recognition (varying ring voltage and frequency)
- Sleep mode / lower power status of modems

Based on the test plan, the Phase I - III tests were conducted to evaluate the performance of the modems. The results from Phases I – III indicated that generally the modems performed similarly with few exceptions regardless of chipset or manufacturer. Therefore Phase IV was reduced somewhat and the tests focused more on differing attenuation and noise levels in each direction of the phone lines. Appendix C lists the tests performed and the details of the experiments conducted and results of each experiment. The observations from each phase of the tests are summarized in the following section.

3.3. Analysis of Modem Test Results

The test plan described in Section 3.2 was conducted and multiple tests were performed on the modems listed. The results of individual tests are listed in Appendix C. The information gathered and conclusions derived from each phase of the tests are presented in the following sections.

<u>Phase I. – Compatibility Tests, Ideal Line Conditions:</u>

From the tests, mentioned in Appendix C, under ideal conditions all modem performed to the desired specs. *All modem pairs communicated at the optimum speed that is compatible with both modems and compression helped in cases where the files where not compressed.* The test results indicate that the modems with different chipsets, maximum transmission speeds or manufacturers are still compatible in the basic sense (no line impairments).

Some large files were transferred between modems during the initial tests to examine transfer rates and compression. It was noted that the compression in the V.42bis standard performed better than that in the MNP 5. Also, it was found that the serial line connecting the PC to the modem should be set for its maximum transfer speed (autodetect the maximum of the modem) for the fastest file transfer. Note that this is the default configuration of almost all PC serial ports.

<u>Phase II – Noisy Line Performance Tests:</u>

The tests of modem performance over noisy line conditions were performed as described in the test plan. Most available combinations of modems were tested initially, but in latter tests the desktop modems combined with DC modems were emphasized. The individual test results are presented in Appendix C. Table 2 summarizes the results of the tests under equal noise conditions in both communication directions (the most likely condition on telephone lines). The noise produced by the Teltone TLE is white noise and the units are dBrn. The unit dBrn is noise level in decibels relative to a reference level of –90 dBm (decibels relative to a milliwatt; -90 dBm = 10^{-9} milliwatts = 10^{-12} Watts).

Table 2. Maximum Operating Noise Level (in dBrn)

CALLING MODEMS	**RECEIVING MODEMS**											
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
A	60	60	55	60	55	60	65	60	60	60	NP	NP
B	60	NA	60	60	60	60	60	50	60	60	60	60
C	60	60	NA	60	60	60	60	55	60	60	NP	NP
D	60	60	60	60	55	60	60	55	60	60	55	50
E	60	60	60	55	NA	60	60	60	55	NA	NP	NP
F	60	60	60	60	60	60	60	60	60	60	55	60
G	55	50	60	60	60	60	NA	60	60	60	60	55
H	60	60	50	55	60	60	60	NA	60	60	55	65
I	60	60	55	60	50	60	60	60	NA	60	60	65
J	60	60	60	60	NA	60	60	60	60	NA	NP	NP

NA = Combination of modems not available.
NP = Tests of this combination of modems not performed.

Modem Key
A - Starcomm 14.4 (Rockwell)
B - LPM 14.4 (Rockwell)
C - Cascade 14.4 (Rockwell)
D - Starcomm 33.6 (Rockwell)
E - Cascade 33.6 (Rockwell)
F - Micro-Aide 33.6 (Rockwell)
G - Best Data 56 k (Rockwell)
H - US Robotics (USR)
I - Zoom 56 k (Lucent)
J - Laptop 56 k (Lucent)
K - Motorola V.3600 (Motorola)
L - Telenetics MIU 14.4 LV (Rockwell)

The results summarized in Table 2 demonstrate that most modem combinations performed very similarly with respect to added noise. Most were able to connect and communicate with added noise levels up to 55-60 dBrn (-35 to -30 dBm). A few combinations (shaded in green) performed slightly better and were able to tolerate a noise level of 65 dBrn. Even the least resilient combinations (shaded in yellow) were able to connect and communicate with noise levels up to 50 dBrn (-40 dBm). All but one of these least resilient combinations consisted of a 56K modem attempting to communicate with a 14.4 or 33.6K modem. This is likely due to the optimization of 56K modems for commercial use at higher speeds at the expense of performance at lower speeds.

One note that should be mentioned here is that 56K modems can only operate above 33.6K if communicating with digital modems such as those used by local internet service providers (ISPs). Two 56K modems can only communicate at speeds up to 33.6K since this is the highest analog modulation available. The modulation used to communicate at 56K is a pseudo-digital modulation that can only be used to transmit data from a digital modem to a 56K modem; communication from the 56K modem to the digital modem (to the ISP) is limited to the 33.6K analog modulation speeds (see Appendix A). *Therefore, it is not useful to upgrade the modems used to collect data from the TTMS sites (those in the Burns Building) to modems with rates higher than 33.6K.*

A variation on the above tests was performed to test the compatibility of 56K modems with lower-rate DC modems. In this test, the noise on the calling modems was fixed at a level of 55 dBrn, and the noise of the receiving modems was varied. The maximum receive noise where a connection could be established was recorded. The results of this test are summarized in Table 3. Note that the most important result from this test is that the 56K modems often have reduced performance when used with (especially calling to) 14.4K modems. *Therefore it is not a good idea to use standard 56K modems to collect data from the TTMS sites.*

Table 3. Constant Noise of 55 dBrn on Calling Modems

CALLING MODEMS	**RECEIVING MODEMS**						
	A	**B**	**C**	**D**	**E**	**F**	**G**
A	65	60	60	65	60	60	65
B	55	NA	60	65	60	60	65
C	60	60	NA	60	60	60	NC
D	55	60	55	NA	65	65	65
E	60	NC	60	60	NA	65	60
F	60	55	NC	60	60	NA	65
G	60	60	NC	60	60	65	NA

NC = No connection could be achieved
NA = Not available combination

Modem Key
A - Starcomm 14.4 (Rockwell)
B - Cascade 14.4 (Rockwell)
C - Cascade 33.6 (Rockwell)
D - Best Data 56 k (Rockwell)
E - US Robotics (USR)
F - Zoom 56 k (Lucent)
G - Laptop 56 k (Lucent)

Phase III – Attenuated Line Tests:

The attenuation of the signal levels was varied for different types of chipsets, protocols and manufacturer to evaluate the performance of modems under noise-less line conditions. These tests were intended to determine the ability of the various modems to adjust to attenuated line conditions such as those that might be experienced on telephone lines to more remote TTMS locations. The test procedures were similar to those of Phase II, except that line attenuation values were modified and no noise was added to the line. The complete test results are given in Appendix C. A summary of the results using equal line attenuation in each communication direction is given in Table 4.

All of the modem combinations operated with line attenuations up to 24 – 34 dB. The combinations least able to withstand line attenuation (only 24 dB) were the US Robotics 56K modem with either the Cascade or Starcomm 14.4K modems. In contrast, the combination able to operate with the most line attenuation was the Best Data 56K modem with the Starcomm 14.4K modem. The remainder of the tests showed no distinct trends or patterns indicating preferences of modem chipsets or manufacturers. Other than the examples mentioned above, even the top speeds of the modems seemed to have no impact on the performance of the modem pairs. Any modem that operates consistently with attenuation of 30 dB or more will likely operate well.

Again, a variation of these tests was conducted using a fixed attenuation of 28 dB on the calling modems. Then the maximum attenuation on the received modem was varied in order to determine the maximum attenuation where connection was possible. As in Phase II, these results were determined before the Motorola, Telenetics and Micro-Aide modems were available. The results, shown in Table 5, again simply reflect the reduced performance of 56K modems with low-speed (14.4K) modems. All other combinations of modems had very similar performance.

Table 4. Maximum Operating Line Attenuation

CALLING MODEMS	RECEIVING MODEMS											
	A	B	C	D	E	F	G	H	I	J	K	L
A	30	28	32	30	28	32	34	24	28	28	NP	NP
B	28	NA	30	28	30	30	30	30	26	28	32	28
C	30	30	NA	26	28	30	32	26	30	28	NP	NP
D	30	28	30	30	26	32	30	30	32	30	32	28
E	32	30	28	26	NA	30	30	28	28	NA	NP	NP
F	32	30	30	32	30	30	30	30	30	32	32	30
G	30	30	30	30	30	30	NA	30	28	28	30	30
H	28	30	24	30	32	30	30	NA	28	28	30	32
I	28	26	28	32	26	30	28	30	NA	30	28	30
J	30	28	28	30	NA	32	30	30	30	NA	NP	NP

NA = Not available modem combination.
NP= Test not performed with this combination.

<u>Modem Key</u>
A - Starcomm 14.4 (Rockwell)
B - LPM 14.4 (Rockwell)
C - Cascade 14.4 (Rockwell)
D - Starcomm 33.6 (Rockwell)
E - Cascade 33.6 (Rockwell)
F - Micro-Aide 33.6 (Rockwell)
G - Best Data 56 k (Rockwell)
H - US Robotics (USR)
I - Zoom 56 k (Lucent)
J - Laptop 56 k (Lucent)
K - Motorola V.3600 (Motorola)
L - Telenetics MIU 14.4 LV (Rockwell)

Table 5. Fixed Attenuation at 28 dB on Calling Modems

CALLING	RECEIVING MODEMS						
MODEMS	A	B	C	D	E	F	G
A	32	32	32	30	NC	32	36
B	30	NA	28	32	NC	30	30
C	32	28	NA	32	30	30	NC
D	30	30	30	NA	32	30	32
E	28	NC	30	32	NA	32	32
F	26	28	NC	30	30	N A	30
G	28	28	NC	32	30	30	NA

Modem Key
A - Starcomm 14.4 (Rockwell)
B - Cascade 14.4 (Rockwell)
C - Cascade 33.6 (Rockwell)
D - Best Data 56 k (Rockwell)
E - US Robotics (USR)
F - Zoom 56 k (Lucent)
G - Laptop 56 k (Lucent)

NC = No connection could be made
NA = Not available combination

Phase IV –Combination of Impairments and Focused Tests:

Combination of Impairments:

After analyzing all the results from the previous phases it was determined that there is in general no consistent difference between using combinations of modems with different or the same manufacturers or chipsets. The biggest discernable drop in performance came when 56K modems are used in conjunction with the lower speed DC modems, particularly the 14.4K modems. To further explore this effect, the 56K modems were used to call and make connection with the available 14.4 and 33.6K modems under a combination of noise and line attenuation. For this test, the attenuation in both directions was fixed at 24 dB (the lowest successful connection speed in Phase II). The noise in both directions was then varied to determine the maximum noise level at which the modems can establish a connection. The results of these tests are summarized in Table 6.

The results of the test for most combinations of modems indicated that the connections could be established with noise levels between 38 and 42 dBrn, a very consistent result. This level is below the levels recorded in Table 2 due to the 24 dB added attenuation. The US Robotics 56K modem was much more sensitive to the noise (connected only up to 30 dBrn) when communicating with a couple of the 14.4K modems. This is due to the attenuation being at or near the maximum allowed for these combinations of modems.

These results further demonstrate that the 56K modems are not a good choice to use for polling the TTMS data sites, especially those sites with lower speed modems.

Table 6. Combination of Noise and Attenuation: 56K with Lower-Speed Modems

Desktop Modems	DC MODEMS							
	A	B	C	D	E	F	G	H
BestData 56k	42	42	42	42	44	44	42	44
US Robotics 56k	42	30	30	40	38	44	40	40
Zoom 56k	40	42	40	42	40	44	40	40

Modem Key
A - Starcomm 14.4
B - Cascade 14.4
C - LPM-14-E
D - Cascade 33.6
E - Telenetics 14.4 MIU-LV
F - Motorola V.3600
G - Starcomm 33.6
H - LPM - 33

Focused Tests of Actual Telephone Lines:

A few basic tests were conducted to check the performance of modems on different telephone lines. In these tests, four different 56K modems with three different chipsets (Lucent, Rockwell/Conexant and US Robotics) were tested to see which modems gave the best tolerance to actual telephone line conditions. The four modems were each used to connect to three different dial-up Internet access points from four different locations (test sites). For the most part, the modems performed similarly at each location. However, the performance varied significantly between test site locations. No significant performance differences between the modem chipsets can be concluded from these brief tests. It was noted that the connections called from the FDOT facility at Springhill Road had some of the lowest connection speeds. The reasons for the performance at the Springhill Road facility cannot be conclusively identified at this time. The reasons may include local wiring, connection to local wire center, digital conversion at the wire center, etc. Variations like these observed in the tests are not uncommon. The detailed results of these experiments are list in Appendix C.

To further expand on the analysis of variations in telephone lines, further testing was performed using a pair of Modem Line Quality Testers (MLQT). These devices are attached at two different telephone lines. The MLQT at the source end dials the MLQT at the destination end and the connection is negotiated like a standard 28.8K modem. These devices then send known patterns of data to each other and record the error and time of good data transfer. The resulting information gives a good indication of the quality of the connection.

The MLQTs were used to check line quality between several line different telephone lines at different locations: one line at the FAMU-FSU College of Engineering, six lines at the FDOT the Springhill Road facility and the 8 modem lines used for data collection at the Burns Building. The modem line in Dr. Harvey's office was used as the destination number for all the tests in order to provide a common reference. The results of these tests are listed in Table 7.

Table 7. MLQT Test Results

Test No.	MLQT	Location	Telephone Number	Total Bytes Sent	# Error Bytes	Percent Byte Error	Total Duration (seconds)	Error-Free Seconds	% Error-Free Seconds	Connect Speed	Signal Level (dB)	Signal Quality
1	S	COE Rm 322	410-6435	331914	0	0	120	120	100	28800	21	16
	D	Dr. Harvey's office	410-6675	332094	0	0	126	126	100	28800	19	17
2	S	Springhill Telco lab	414-2813	227463	0	0	120	120	100	21600	24	17
	D	Dr. Harvey's office		227603	18	7.91E-05	117	116	99.14	28800	22	28
3	S	Charles Goff Off.	487-0975	175654	8330	4.0742	120	115	95.83	21600	25	23
	D	Dr. Harvey's office		176761	9366	5.298	91	85	93.4	26400	25	20
4	S	Jonathan's Off.	413-7691	309183	0	0	120	120	100	26400	24	28
	D	Dr. Harvey's office		309361	0	0	126	126	100	26400	24	20
5	S	Tom Porter's Off.	922-8006	286024	0	0	120	120	100	24000	25	23
	D	Dr. Harvey's office		286188	0	0	125	125	100	28800	22	24
6	S	Testing Room	922-8006	294292	9	3.66E-05	120	119	99.16	26400	27	28
	D	Dr. Harvey's office		294468	16	5.43E-05	119	118	99.15	28800	25	30
7	S	Testing Room # 2	414-2812	273891	0	0	120	120	100	24000	24	18
	D	Dr. Harvey's office		274055	15	5.47E-05	120	119	99.16	28800	22	30
8	S	Student's Apt	224-8959	272289	0	0	120	120	100	24000	22	17
	D	Dr. Harvey's office		272460	20	7.34E-05	119	118	99.15	26400	21	26
9	S	Burns Building #1	414-2701	227116	56	4.66E-04	120	117	97.5	21600	24	13
	D	Dr. Harvey's office		227464	142	6.24E-04	117	113	96.58	26400	24	28
10	S	Burns Building #2	414-2702	284882	9	3.16E-05	120	119	99.16	24000	21	20
	D	Dr. Harvey's office		285049	9	3.16E-05	125	124	99.2	26400	25	31
11	S	Burns Building #3	414-2703	284628	0	0	120	120	100	24000	22	18
	D	Dr. Harvey's office		284796	0	0	125	125	100	24000	24	17
12	S	Burns Building #4	414-2704	272385	57	2.09E-04	120	116	96.66	24000	24	25
	D	Dr. Harvey's office		272556	46	1.69E-04	119	116	97.47	26400	24	26
13	S	Burns Building #5	414-2705	226338	39	1.72E-04	120	119	99.16	21600	24	15
	D	Dr. Harvey's office		226688	129	5.69E-04	116	113	97.41	26400	24	22
14	S	Burns Building #6	414-2706	271212	10	3.69E-05	120	119	99.16	24000	24	23
	D	Dr. Harvey's office		268821	27	9.95E-05	119	117	98.31	26400	24	26
15	S	Burns Building #7	414-2707	284451	0	0	120	120	100	24000	24	24
	D	Dr. Harvey's office		284618	0	0	125	125	100	26400	24	25
16	S	Burns Building #8	414-2708	227778	0	0	120	120	100	21600	24	15
	D	Dr. Harvey's office		227925	18	7.90E-05	117	116	99.14	26400	24	28
17	S	Burns #1 (Repeat)	414-2701	226791	19	8.38E-05	120	118	98.33	21600	24	14
	D	Dr. Harvey's office		226932	36	1.59E-04	117	114	97.43	26400	24	33

MLQT = Modem Line Quality Tester
S = Source of Call
D = Destination (where call was received)

The results of these tests indicate considerable variability even among phone lines from the same building. The one line tested at the FAMU-FSU College of Engineering performed flawlessly which can be expected since the call connection likely didn't leave the building. At the Springhill facility almost all line had very few or no errors. The one exception is the line in Charlie Goff's office that had a high number of errors (an error rate of nearly 7% in one direction). The cause of the errors is unknown, but it corresponds with the difficulty Mr. Goff has had with connecting to some TTMS locations. At the Burn's building, all of the line performed reasonably well with only a couple of lines having an error rate approaching 3%. One of these lines was re-tested and it performed slightly better, but still had several errors in both directions. The MLQTs can be used to identify lines with poor conditions for modem performance, but to get a good picture of the line's quality these tests may need to be repeated ~20 times to isolate statistical variations.

4. MODEM INITIALIZATION STRINGS

Many users ask for optimal initialization strings for their particular modem, and many are posted on bulletin board services (BBSs) and newsgroups. If one takes the time to learn some of the basic features available in most modems, one can see that these strings are merely a series of commands that enable, disable, or specify parameters for these features. Most modem manufacturers choose reasonable default values for these features in hopes that the modem will be usable with little or no configuration. Unfortunately these defaults vary from one brand (or model) of modem to another, and settings will depend on the features of the computer and communications software, as well as those of the system one wishes to call.

An AT string is a set of commands that control the modem. The default strings come as part of the modem's factory settings. There are two ways to configure a modem: storing the configuration in the modem or storing initialization strings in one's communications software. The former is generally simpler, but not a feature of all modems. The latter can be more cumbersome, but allows for greater flexibility in allowing different configurations for calling different services.

Here are a few examples:
AT S0=0 &B1 &H1 &W
Set no answer, CTS flow control, fixed DTE (serial port) rate, and store the configuration on a U.S. Robotics modem such as a Courier or Sportster.

AT S0=0 &K3 &W0
Set no answer, hardware flow control, and store on a modem based on the Rockwell RC144AC chip set such as the Gateway Telepath.

Appendix E gives some of the common AT commands used.

4.1. FDOT Experiences with Modem Strings

The FDOT Transportation Statistics Office has considerable experience in using modems to collect data from the TTMS traffic monitoring equipment. There is a fairly large number of modem types used to collect data from traffic monitoring equipment from various manufacturers (primarily Peek, PAT and Diamond). The data collected daily varies from simple count summaries to large files containing weigh-in-motion measurements. A large percentage of the modems are connected to standard telephone wires, with only a few connected through cellular connections. This discussion will focus on the majority of the modems connected to the telephone lines though much of the discussion is applicable to cellular modems as well.

The typical procedure used by the FDOT when deploying a new modem type is as follows. First, one of the new modems is sent to the manufacturer of the traffic monitoring equipment to which the modem is to be attached. The manufacturer tests the modem and determines the appropriate modem string or strings required to properly configure the modem to operate with the traffic monitoring equipment and the corresponding data collection software. The modem and modem strings are sent back to the FDOT and the modem is deployed using these strings.

Relying on the manufacturer of the traffic monitoring equipment to determine the appropriate modem string seems a logical step in the deployment of a new modem. However, the results of this procedure have been mixed. For example, Figure 2 demonstrates a modem string designed to be used on a Starcomm 14.4K modem connected to a Peek ARD3000 (and the Peek data collection software).

```
ATQ0
ATV1E0F0L0N1W2M1
AT&C1&D2&K0&Q5&R1
AT\A3\G0\N6
AT%C3%E1
ATS0=1S24=120S7=90
AT&W0
```

Figure 2. Modem String for Starcomm 14.4K Modem on Peek ADR3000

The modem string in Figure 2 contains fairly standard modem commands. The interesting commands, however, are the commands in red and blue in Figure 2. First, all the commands listed in blue are defaults for the modem and are typically set using the command ‘AT&F0’; this command can be automatically sent by the data collection software instead of the strings listed in Figure 2, and is typically set by the field technicians when setting up the modems connected to the traffic monitoring equipment. Therefore, all these commands in blue are redundant and can only lead to more human errors, especially setting up the remote modems in the field.

The command in red, ‘F0’, instructs the modem to autodetect the telephone line modulation *unless the automode is enabled* (using the ‘N1’ command listed later in the same line). Therefore, the ‘N1’ command supersedes the ‘F0’ command making the latter command have no effect. (Special note: The ‘Fx’ commands are only valid in the 14.4K modems, not the newer 33.6K modems.) Also, note that the ‘N1’ command is the modem default and is not needed either.

The remaining commands in the modem string actually do change the operation of the modem, though some have no effect on the connection and transmission of data. The ‘E0’ command shuts off command echo (i.e. AT commands not echoed back) and the ‘W2’ command instructs the modem to report the DCE speed (speed of the serial connection) rather than the modulation speed; neither of these commands affects performance of the modem connection. The ‘\A3’ command sets the block size to maximum for the error correction used in the MNP protocols (may modestly improve the transfer rate, but reduces error correction and detection). The '%E1' command allows the modem to renegotiate the modulation parameters if changing line conditions make it necessary; this is unlikely on a fixed phone line, but may be more useful on a cellular modem. The command 'S0=1' sets the modem to answer on the first ring; this is required for the field modem (all modems tested are set to not answer the phone by default). The command 'S24=240' instructs the modem to go into sleep mode 2 minutes after disconnect, and 'S7=90' allows the modem to attempt to connect for up to 90 seconds after answering (default is 50 seconds).

The remaining command '&K0' instructs the modem to disable all flow control. Flow control is used to regulate the flow of information to avoid overflowing buffers in the modems. Flow control can be handled through software (XON/XOFF) or through hardware lines in the serial connection (CTS/RTS). The typical default setting is to use hardware flow control. When transferring binary files (as the Peek equipment does) the software flow control must be disabled to avoid inadvertent flow control messages being sent. However, the hardware flow control is almost always used. Disabling all flow control can cause problems when transferring large files when the modem connection speed is slower than the serial port speeds connecting the modem to the traffic monitoring equipment or the computer. The engineers from Peek recommend using the '&K0' command and that advise will likely work. However, if problems continue, especially with long file downloads, restoring the default command '$K3' to enable hardware flow control may be tried.

Tests were conducted with very simple modem strings to see if a connection could be made to a Starcomm modem connected to an ADR3000 in the Springhill Road facility. The string used for the remote modem (connected to the ADR3000) was 'AT&FS0=1S24=120S7=90&Y0&W0' and the string for the data collection modem was 'AT&FS7=90&Y0&W0'. These strings simply restored defaults, set up the modems registers, saved the settings in profile 0, and set profile 0 to default after modem reset. The data collection modem was then used to call the remote modem using the Peek software. The connection was successful and simple communication with the ADR3000 was achieved. No traffic data files were on the ADR3000 so no binary file download was possible with this test to verify the need or lack of need of the '&K0' command.

This modem string in Figure 2 was sent to Starcomm engineer Octavio Reza for comments. He suggested the modem string in Figure 3 for future use with the Starcomm 14.4K or 33.6K modems. Mr. Reza was also curious about the need for the '&K0' command and suggested further contact with Peek and experimentation to determine if removing all flow control is truly needed.

AT&F&W1&W0
ATS0=1S24=120S7=90
AT&K0
ATE0&Y0&W0

Figure 3. Modem String Recommended by Starcomm

In contrast to the Peek modem string, the Diamond modem strings are considerably different. The Diamond modem strings are the same regardless of modem. A set string is used by the host or data collection modem. A fixed modem string and a variable modem string are programmed into the traffic monitoring equipment for the remote modems. The strings used by the FDOT are listed in Figure 4.

Host Modem String:	AT&F&C1&D2M1L1\Q0
Fixed Remote Modem String: (Modem Setup Command #1)	ATE0Q0V0S0=2
Variable Remote Modem String: (Modem Setup Command #2)	ATX1&C1&D2

Figure 4. Modem Strings Used for Diamond Equipment

As in the Peek modem strings, several of the commands are defaults in most modems (shown in blue). Most of the remaining commands have to do with setting the modem to answer on the second string ('S0=2'), result codes, the modems speaker and echo off. The only unusual code found is '\Q0'. This command does not appear in the modem instruction sets received with the modems tested in this project. A couple of modem books listed this instruction as the command to disable flow control (similar to '&K0'). Since most modems do not recognize this command, it should have no effect on the modems and the default hardware flow control should be in effect. Note that this command may actually be a typographical error and the 'Q0' command (default command to enable result codes) may have been intended.

Recommendations on Modem Strings

Modem strings should be kept as simple as possible to achieve the desired modifications to the modem function without the repetition of default commands. Modems currently being produced have most capabilities and modem commands in common. Those commands specific to the modems are typically for non-standard enhancements such as the MNP 10 protocol for cellular phones, and these enhancements typically are not needed.

Modems strings, where possible, should begin with a modem reset ('&F') to factory defaults and then it should be stored in the modem profiles (both profiles 0 and 1 recommended by the Starcomm engineer). The S-registers should be set to utilize the modems power saving capability (if available) and in the remote modem they should be set to allow the modem to answer the phone ('S0=x' where x is the ring number to answer). Most modem strings from the traffic monitoring equipment manufacturers recommend disabling command echo and thus this should also be done.

It should be verified that software flow control is disabled (standard on all modem checked) unless specifically requested by the specifications of the traffic monitoring equipment. This is especially important if the equipment transmits binary data files (e.g. Peek equipment). The disabling of hardware flow control is a questionable practice and should be investigated further with the Peek engineers. It is highly unusual that the hardware flow control lines are disabled or nonexistent on a serial port.

Finally, the settings should be saved in the modem's profile, preferably profile 0 (default profile on power-up and reset). A recommended modem string for Starcomm modems was provided by the Starcomm engineer and is listed in Figure 3. The need for the '&K0' command needs to be verified. Otherwise, this modem string, with only minor modifications to the S-registers, should be compatible with most modems and most traffic monitoring equipment.

5. RECOMMENDED STANDARDS FOR MODEMS

The goal of this project was to establish standards for the purchase of modems for use in the collection of traffic monitoring data. The tests of physical performance and the use of modem strings have led to a set of recommendations for purchasing requirements. These recommendations are listed below along with justification and verification tests.

Protocols and Operating Speeds

The modems purchased should be able to operate using all modulation protocols listed in Table 1 up through as a minimum V.32bis (14.4K), but preferably V.34 (28.8K) or v.34bis (33.6K). Modems operating at the V.90 protocol (56K) are not needed and may in fact have worse performance when attempting to communicate with a 14.4K or slower modem. It is NOT recommended that 56K modems be used at either the data collection or remote sites. Note that all modems tested were compatible with all slower speed protocols and thus a modem only need to be specified by its maximum operating speed.

The serial ports on much of the traffic monitoring equipment in use are actually slower than the modem maximum rate. This should not dissuade the use of higher speed modems as the higher speed modems will affect the communication significantly and may in fact slightly reduce the time to transmit the data. In general, the time required to transmit the data is limited not by the modem connection, but more often by the processing requirements and capabilities of the traffic monitoring equipment. As the manufacturers improve the processing capabilities and serial ports speeds in the future, the use of higher speed modems will reduce download times and thus reduce phone costs.

Communication Performance Specifications

The test results from Phases II and III above generally indicate that most modem combinations perform nearly the same. Even using two identical modems does not consistently have better performance than using modems from different manufacturers or having different modem chipsets. The only recurring combination having performance problems was the combination of a 56K modem with a 14.4K modem; this is a common problem with the popular and highly rated US Robotics 56K modems. Thus it is recommended that 56K modem not be used.

The tests of noise and attenuation did result in some expected performance levels for modems and thus specifications and requirements can be made for the future purchase of modems. These specifications are

1. Each modem purchased must be able to connect with equal (same in both directions) white noise levels of at least 55 dBrn (-35 dBm).

2. Each modem purchased must be able to connect and operate with equal attenuation levels of at least 28 dB.

These specifications can be verified using the test procedures described in Appendix D. These specifications must be met when the purchased modem is communicating with all types of modems for which it is intended to communicate. For example, all modems purchased for use in the TTMS sites must meet these specifications when tested in combination with all modems used in the Burns building for collecting the traffic data. Conversely, new modems purchased for use in the Burns building should meet these specifications when tested in combination with most if not all of the modem types used in the TTMSs.

Combinations of noise and attenuation only confirmed the weaknesses and strengths of modems that were evident in the individual noise and attenuation tests. Therefore combinations of impairments need not be specified or tested when purchasing new modems.

Data Compression and Other Specific Protocols

Virtually all modems of 14.4K speed or higher also include the V.42bis and MNP 5 protocols to add data compression. The V.42bis can compress up to 4-to-1 and the MNP 5 up to 2-to-1. This compression will generally have less effect on binary files and maximum effect on ASCII files. The V.42 protocol, also commonly available, provides some added error protection. The default settings for any or all of these protocols will provide good modem performance. If the choice is given, generally V.42bis will have higher compression (and thus faster data transfer) than the MNP 5 protocol.

For use on cellular modems or modem used over cellular or other wireless connection, the inclusion of special protocols to allow the modem to withstand the varying channel conditions are very important. The most common protocols are MNP 10 and MNP 10EC. In addition, some modems in the past have included MNP 10ETC. Note however that these protocols are NOT accepted standards observed by all modem manufacturers. To use these protocols the modems at both ends of the connection must be capable of the same protocols. All the modems tested with these special protocols were however able to negotiate the connection with modems that do not have these protocols without any special setup commands. Therefore, a modem that has MNP 10 or other special protocol need not be restricted to use on connections with other modems with similar protocols.

Initialization Strings

While not actually a specification to be considered, the initialization string has been a source of problems for the FDOT and others when connecting modems for remote data collection. The study and experimentation discussed previously does lead to some important results that need to be considered:

1. Modems should be reset to factory defaults before configuration. (It is recommended to store in profile 0 as well.)

2. Modems at the TTMS locations need to be configured to answer the phone when it rings (e.g. 'ATS0=1').

3. Systems that transfer binary files need to ensure that software flow control is disabled; this is default in all modems tested.

4. Special functions such as power saving or cellular protocols need to be enabled.

5. Repeating factory defaults in the modem string should be avoided to reduce errors.

6. The settings should be saved in profile 0 (the default reset profile).

The initialization string is probably the most common cause of connection problems. Common problems are typographical errors and the use of custom modem commands on the wrong modems. Virtually all, necessary settings are standard modem commands recognized by all modems. Sometimes it is possible to improve performance by adding to or changing the initialization string to include specific, non-standard features of a modem; these features need to be checked on a case-by-case basis.

Physical Specifications

The general physical properties of modems were not directly addressed by this effort, but the modem survey and the requirements of TTMS modems lead to the following recommendations for physical specifications.

Voltage: The remote modems must be capable of operation with a 12 V DC power supply without external voltage converters.

Power Requirements: The remote modems are typically powered solely by solar cells and batteries and thus the current demands of the modem are significant. Also, the modem typically operates for less than 1 hour each day and the modem should be capable of switching to a low-power sleep or standby mode of operation (awakening on receiving a ring signal). The recommended requirements for maximum current (at 12 V operating voltage) is 300 mA for operating (communicating) and 25 mA for standby or sleep mode. These levels are available for a number of modems surveyed.

Operating Temperature: The remote modems are subjected to a far wider range of temperatures than typical desktop modems. The remote modems are not subject to direct sunlight, but the TTMS cabinets are not climate controlled. The recommended operating range for the remote modems is -20°C (-4°F) to +70°C (+160°F). For colder climates than Florida, it may be preferable to low the minimum operating temperature to -40°C (-40°F).

Connectors: The power connector for the modem must be external and capable of connecting to wires up to 16 gauge. The telephone line connector must be a standard RJ-11 modular telephone line jack. The serial connector must be a female DB-25 connector (EIA-232 DTE).

Chipsets: The specific manufacturer of the modem's chipset was not found to significantly affect the interoperability of the modem. Therefore, no chipset(s) are specified.

Summary of Recommendations

The recommended specifications for the remote (DC-powered) modems are summarized in Table 8. These specifications are applicable to the AC-powered modems with the exception of the power, voltage and operating temperature requirements. The specifications are divided into two categories: standard specifications and performance specifications. Standard specifications are those typically listed in the documentation for the modems. The performance specifications are those associated with line attenuation and noise levels tolerated by the modems. The performance specifications were derived from the results of the tests performed under this effort.

Table 8. Recommended DC Modem Specifications

PARAMETER	VALUE	COMMENTS
Standard Specifications		
Operating Voltage	12 V DC	No adaptors or converters.
Maximum Current	300 mA (operating) 25 mA (standby or sleep)	
Operating Temperature	-20°C to +70°C	
Connectors Power Telephone Line Serial Port	 External (up to 16 gauge) RJ-11 Female DB-25	 No special connectors. Telephone modular jack. EIA-232 DTE.
Operating Speed	V.32bis (14.4K) minimum, V.34 (28.8K) or v.34bis (33.6K) preferred.	NOT V.90 (56K) or other 56K protocol.
Other Protocols Compression Cellular Specific	 V.42bis MNP10, MNP10EC or MNP10ETC	Cellular protocols only for cellular applications. There must be a compatible modem at each end.
Performance Specifications		
Line Attenuation	Must operate up to 28 dB attenuation	Attenuation the same for both communication directions.
White Noise	Must operate with at least 55 dBrn (-35 dBm) of additive white noise.	Noise on both directions of communications.

6. CONCLUSIONS

The testing and analysis of modems have lead to some expected and some surprising results. Modem chipsets seemed to have very little influence on performance, as the chipsets seemed to be compatible with each other. Most modems performed similarly under ideal and impaired line conditions with only a few seeming to have increased sensitivity to noise or attenuation. Therefore testing of the modems will be a process of eliminating the poorer performing modems rather than identifying the few “good” performing modems. Also found was that the newest 56K modems seemed to have more performance problems communicating with lower speed modems (14.4K and below) than other modems. Since 56K speed cannot be used from modem to modem, it was therefore recommended that 56K modem NOT be used for this application. As discussed in Section 3.3, the 56K speed is not useful in this application and thus this is not a severe restriction.

An investigation of modem strings was added to the project to determine the impact of these strings and to investigate minimum strings needed. It was found that the modem strings used contained multiple redundant commands that simply repeated very common modem default settings. The analysis indicated that virtually all modems could use the same command string for each type of traffic monitoring equipment.

Recommendations for future modems have been listed in Section 5 and the detailed test procedures to verify the physical performance of the modems is given in Appendix D. The equipment purchased for this project, including the Teltone telephone line emulator, is the property of the FDOT and thus will be available for modem testing.

APPENDIX A - MODEM CHIPSETS AND MODULATION PROTOCOLS

A.1 Modem Chipsets

One of the factors that would enable the user in making sure that the modems used at the two ends are compatible is to ensure that they are compatible. Since there are hundred of modem manufacturers, vendors, OEMs (*Original Equipment Manufacturer*), and distributors that sell "different" modems it might seem that it is impossible to ensure for compatibility. Fortunately there are only a handful of "chipsets" and once the chipsets are known it is much easier to make sure that the modems would be compatible with similar modems at the other end. This can also help in upgrading the modem without needing to find the users specific brand and model. Below is a compilation of information on modem chipsets uncovered using a search of modems and modem handbooks.

KNOWN CHIPSETS:

TERMINOLOGY:

HSP: Host Signal Processor (HSP) *modems* use fewer and cheaper chips compared to traditional modems. The work normally done by the missing chips is transferred to software running on the host computer's main processor (the Pentium, PowerPC, etc) hence called HSP.

Note: A popular synonym for HSP modems is "controllerless modems."

DSP: Digital Signal Processor (DSP) modems are one of the highest performance modems as they have a "Controller" on-board to process commands and to handle error-correction and data compression. Modems without a Controller (i.e. HSP) shift all this processing to your PC's processor as mentioned above. Flash Memory is one sure sign that a modem has a Controller.

Note: There are modems that have DSP chips but the controller functions are software based. This situation usually arises when a certain manufacturer makes the chipset and the vendor is someone who tries to combine different chips and make a modem. Examples of such a DSP chips are the variety of Lucent DSP chips used by vendors to make modems. This kind of modem is not recommended because the software does not guarantee to support all modem functions. Standalone modems are virtually all DSP modems and thus this is not a serious issue for the FDOT data collection.

Broadcom:
BCM - Software PCI HSP modem.

Conexant / Rockwell:

Rockwell, now Conexant, doesn't make modems - they make chipsets and develop the firmware/drivers and sell them to various modem manufacturers. The "HCF" chipset is actually a single-chip PCI software-modem (controllerless, aka (also known as) “Win Modem”).

ACF - Hardware controller; requires firmware flash from modem vendor.
HCF - Software modem w/ DSP
HSF - aka **Soft56**; Host signal processor software modem.

ESS Teledrive:
ES56x - Host signal processor software modem.

Lucent:
Apollo/Mars - Software modem w/ DSP
Venus - Hardware controller; requires firmware flash from modem vendor.
Scorpio - Host signal processor software modem.
Wildwire - Software modem w/ DSP; combo Analog & DSL Modem.

Motorola:
SM56 - Host signal processor software modem; made in PCI and AMR (audio modem riser) versions.

PC-Tel:
HSP - Host signal processor software modem made in PCI, ISA and AMR versions.

STMicro GS-Thomson:
Pegas - USB host signal-processor. Also makes an AMR HSP modem chipset.

Texas Instruments (including 3Com/USR):
USR is the last modem chipset manufacturer that also produces its own modems.
TMS320x – USR uses TI chip for the DSP on board controller but then there are other modem vendors that use the TI chip with their own design and hence making a different modem e.g. Cirrus.

Conclusion:
The vast majority of modems come with 3Com/TI, Lucent <u>or</u> Rockwell/Conexant chipsets. Another chipset available for purchase is Motorola. There are a few others including the ESS, PCTel and Cirrus/Ambient chipsets. It is recommended NOT to purchase modem with chipsets other than the three main manufacturers as it is likely a discontinued modem line.

A.2 Modem Modulation Protocols

The modem modulation protocols listed in Table 1 determine the data transmission speeds at which a modem can communicate. These protocols are generally a combination of digital communication modulation schemes and data encoding schemes.

In this section, a brief overview of the modulation protocols will be presented. For more detailed information on the modem protocols, the reader may refer to the two references listed below or any of a number of modem books on the market.

References:

- Held, Gilbert, The Complete Modem Reference, Third Edition, Wiley Computer Publishing, John Wiley & Sons, 1997.
- Lewart, Cass R., The Ultimate Modem Handbook, Prentice Hall, 1998.

Also, for the most detailed information on modem protocols, the user may download the standards (recommendations) from the International Telecommunication Union in the Telecommunication Standardization Section (ITU-T). The web addresses are

ITU: http://www.itu.int/home/index.html
ITU-T: http://www.itu.int/ITU-T/
Modem Protocols:
http://www.itu.int/rec/recommendation.asp?type=products&lang=e&parent=T-REC-V

Modulation protocols for the modems translate the digital data to be transmitted into analog signals called symbols. Typically, and integer n data bits are mapped into each symbol. Thus there must be $m = 2^n$ distinct symbols to accommodate all possible combinations of n bits. The baud rate, B, is the rate at which the symbols are transmitted. The resulting data rate for the modulation protocols is $R = nB$. In older, slower modem protocols such as Bell 103 $n = 1$ and thus the bit rate R was equal to the baud rate B.

Nyquist's theorem demonstrates that the bandwidth required for a given baud rate $W = B/2$. The public switched telephone network (PSTN) in the United States provides for signals in the frequency range of 300 to 3300 Hz. Thus the maximum bandwidth for a modulated signal is 3000 Hz and thus the absolute maximum baud rate for a modem is 6000 baud. Since many modems transmit data at a higher rate than 6000 bits per second (bps), it is obvious that modern modem protocols are designed with $n > 1$. In fact, the range of baud rates used in analog modems ranges from 600 (Bell 212A) to 2400 baud (V.32 and V.32bis). The baud rate is less than half the maximum allowable baud rate to allow for full duplex communication. Note that V.90 uses a hybrid digital/analog modulation protocol that will be discussed separately below.

Modems are designed to operate using a specified protocol. In addition, most modems will operate at all or most previous (lower speed) modem protocols. Thus a modem designed to operate using the V.32bis protocol will generally be able to communicate with an older modem designed for the V.22bis standard. The maximum operating speed between the modems will be that of the V.22bis protocol (2400 bps). The ability of modems to communicate with slower modems has been validated by the tests outlined in Sections 3.2 and 3.3 of this report.

The V.90 standard differs considerably from the previous standards for modems. Previous standards assumed that both modems in the communication link will be attached to the local loop of the PSTN. Both modems are assumed to have analog modulation and demodulation capabilities. The V. 90 standard takes advantage of the existence of digital interfaces with the PSTN. Typically a local Internet service provider (ISP) will have a digital interface with the PSTN and will use a digital modem. The ISP user will have an analog modem built to the V.90 standard. The digital modem can transmit up to a rate of 8000 baud (the sample rate of the digital interface) with 7 bits per symbol (n = 7). Thus the maximum transmit rate of the digital modem is 56 kilobits per second (kbps). By regulation the maximum allowed transmission rate is about 53 kbps (related to the maximum average power on the analog lines and bandwidth). In typical use however most users can achieve data rates of 40 to 46 kbps (due to analog line conditions and lengths).

The analog modem built to the V.90 standard does not have the advantage of a sampled digital interface. Thus the analog modem transmits using the V.32bis standard up to a data rate of 33.6 kbps. The result of this hybrid modem implementation is that the ISP user has up to a 53 kbps download speed and a slower 33.6 kbps upload speed. This asymmetrical communication is generally fine for the average internet user dialing into an ISP. If the user were to dial to a location with another analog V.90 modem, the connection will be established using the V.32bis standard and the maximum communication rate will be 33.6 kbps.

The hard wired (non-cellular) FDOT TTMS modems are all connected to analog local loops of the PSTN. Therefore, the maximum transmitted data rates for these modems will be 33.6 kbps. There is no advantage to using V.90 capable modems. In fact, the results of the tests conducted in this effort indicate that there may be a reduction in reliability using V.90 capable modems communicating at lower speeds with other analog modems.

Greater than 33.6 kbps transmission speeds from the TTMS modems over the PSTN can only be achieved by connecting them to digital (ISDN) lines or connecting them to the Internet using a DSL (digital subscriber line) service. Either option is an expensive solution for downloading traffic count and weight information. Typically the transmitted data rate is not currently limited by the modem but rather the traffic monitoring equipments serial port or processing speed. Thus faster modems will have negligible effect on the download speed. However, if high resolution video or other high-bandwidth function is required in the future, the FDOT may have to revisit faster communication options such as ISDN, DSL or non-PSTN options.

APPENDIX B – TELTONE TELEPHONE LINE EMULATOR

The Telephone line Emulator (TLE) is a user-configurable four-port analog telephone emulator, enabling simulation of many public switched telephone network conditions. It is a hardware model (TLE-A-01), and is equipped with software with basic functions. Additional Software purchased includes – Advance Simulations Software Module to perform test like impairments on telephone line, like, echo, white noise, S/N measurements, etc.

The tests that can be performed with the TLE can assist in evaluating the performance of modems based on the parameter like noise in the telephone line, signal to noise ratio, signal level measurements and metering tones. It can also be used to verify if the modem is functioning at all or if it is not compatible.

APPENDIX C - DETAILS OF EXPERIMENTAL RESULTS

C.1. Phase-I Tests

In Phase I the compatibility of all modem combinations was tested. Each modem was configured to factory defaults and connected through the Teltone TLE under ideal line conditions (no noise or attenuation). All combinations of modems connected successfully.

In addition, a few large files were transferred from one modem to the other. Transfer speeds were measured. The results of these tests are listed below.

<u>Test # 1:</u>

Machine 1: Starcomm 14.4 modem (recognized as standard modem – NOT Starcomm)
Machine 2: Win Lucent Modem 56k (Internal – Laptop modem)

Chipset on Starcomm 14.4 modem was <u>Rockwell</u> 93
Chipset on Laptop modem was <u>Lucent</u>

Teltone Parameters: Impedance = 900Ω, Loop Current = 35mA

Attn (dB)	M/C # 1	M/C # 2	Bytes	Time	Thruput (kbps)
4	14400 / LAPM / V.42bis / 19200	14400 / V.42bis	1,528,320	12 min, 47 sec	15.94
26	14400 / LAPM / V.42bis / 19200	14400 / V.42bis	453,786	04 min, 45 sec	12.737
27	14400 / LAPM / V.42bis / 19200	14400 / V.42bis	453,786	04 min, 51 sec	12.475
28	14400 / LAPM / V.42bis / 19200	14400 / V.42bis	453,786	05 min, 00 sec	12.101
29	14400 / LAPM / V.42bis / 19200	14400 / V.42bis	453,786	05 min, 34 sec	11
30	14400 / LAPM / V.42bis / 19200	14400 / V.42bis	453,786	(Disconnected after 10 sec)	
31	No Carrier Detected				

Files Transferred: Sawtooth.avi (1,528,320 bytes) & Lucent_modems_90.pdf (453,786 bytes)

<u>Test # 2:</u>

Machine 1: Starcomm 14.4 modem (recognized as Starcomm)
Machine 2: Win Lucent Modem 56k (Internal – Laptop modem)

Chipset on Starcomm 14.4 modem was <u>Rockwell</u> 93
Chipset on Laptop modem was <u>Lucent</u>

Teltone Parameters: Impedance = 900Ω, Loop Current = 35mA

Attn (dB)	M/C # 1	M/C # 2	Bytes	Time	Thruput (kbps)
4	14400 / LAPM / V.42bis / 19200	14400 / V.42bis	1,528,320	12 min, 47 sec	15.94

File Transferred: 'sawtooth.avi'

This should the same results as test #1. It should be noted though that in the above experiment also the DTE (Data Terminal Equipment) speed was set at 19200. If the speed was set at 57600 then the time it takes to send the file was 4 minutes and 43 seconds. This shows that the DTE speed should always be set to maximum limit in the settings.

C.2. Phase II Tests

In this phase, pairs of modems were connected through the Teltone TLE and the white noise level added to each receive line was varied to determine the maximum noise levels at which the pair of modems could connect and stay connected. For the first 20 pairs of modems the noise level added to each receive line was varied independently. The results of the tests for these pairs of modems are detailed in the tables below ("phase 2 – test 1" through "phase 2 – test 20"). The units of noise in these tables is dBrn or dB relative to noise where 0 dBrn = -90 dBm (dB relative to a milliwatt).

After the first 20 tests were completed it was determined that varying the noise level independently in for each receive line was not necessary. Modems received for testing after these 20 tests were completed were only tested with equal noise levels and only the highest noise level for successful connection was recorded. A table summarizing the maximum noise level (equal in each direction) for all modems tested is provided in Table 2 in Section 3.3.

In addition to the previous tests, additional focused tests were performed to further examine the effects of noise on the modems, especially the combination of 56K modems with lower speed modems. In these tests the attenuation on the calling modems was held fixed at 55 dBrn while the receive modem attenuation was varied. The maximum receive modem noise level where a reliable connection could be achieved was recorded. The results of these tests are recorded in Table 3 in Section 3.3.

		phase 2 - **test 1**		
		M/C 1 = Starcomm 14.4k (**Rockwell**)		
		M/C 2 = **Lucent** Winmodem 56k		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
20	50	14400	14400	
20	55	12000	12000	
20	60	7200	7200	
20	65	4800	4800	54sec
30	40	14400	14400	
30	50	14400	14400	
30	55	12000	12000	
30	60	9600	9600	
30	62	7200	7200	33sec
30	65	4800	4800	34sec
40	20	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
40	30	14400	14400	
40	40	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
40	50	1400	1400	
40	55	12000	12000	
40	60	9600	9600	
50	30	14400	14400	
50	50	12000	12000	
50	58	9600	9600	
50	60	7200	7200	
50	65	4800	4800	33sec
55	30	9600	9600	
55	40	9600	9600	
60	20	4800	4800	
60	30	4800	4800	
60	35	57600/NONE/300/4800/V42BIS	57600/NONE/300/4800/V42BIS	
60	40	57600/NONE/300/4800/V42BIS	57600/NONE/300/4800/V42BIS	
60	45	NO CONNECTION	NO CONNECTION	
60	60	4800	4800	
65	30	NO CONNECTION	NO CONNECTION	

		phase 2 - test 2		
		M/C 1 = Starcomm 14.4k (**Rockwell**)		
		M/C 2 = Starcomm 14.4k (**Rockwell**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
20	40	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
20	50	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
20	55	57600/V32/LAPM/V42BIS/12000	57600/V32/LAPM/V42BIS/12000	
20	60	57600/V32/LAPM/V42BIS/4800	57600/V32/LAPM/V42BIS/4800	
20	65	57600/V32/LAPM/V42BIS/4800	57600/V32/LAPM/V42BIS/4800	42 sec
30	40	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
30	50	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
30	55	57600/V32/LAPM/V42BIS/12000	57600/V32/LAPM/V42BIS/12000	
30	60	57600/V32/LAPM/V42BIS/4800	57600/V32/LAPM/V42BIS/4800	
30	65	57600/V32/LAPM/V42BIS/4800	57600/V32/LAPM/V42BIS/4800	
30	70	No connection	No connection	
40	20	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
40	30	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
40	40	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
40	50	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
40	55	57600/V32/LAPM/V42BIS/12000	57600/V32/LAPM/V42BIS/12000	
40	60	57600/V32/LAPM/V42BIS/4800	57600/V32/LAPM/V42BIS/4800	
40	65	57600/V32/LAPM/V42BIS/4800	57600/V32/LAPM/V42BIS/4800	1min, 2secs
50	30	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
50	40	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
50	50	57600/V32/LAPM/V42BIS/14400	57600/V32/LAPM/V42BIS/14400	
50	55	57600/V32/LAPM/V42BIS/12000	57600/V32/LAPM/V42BIS/12000	
50	60	57600/V32/LAPM/V42BIS/4800	57600/V32/LAPM/V42BIS/4800	
50	65	57600/V32/LAPM/V42BIS/4800	57600/V32/LAPM/V42BIS/4800	
50	70	No connection	No connection	
60	20	57600/V32/LAPM/V42BIS/7200	57600/V32/LAPM/V42BIS/7200	1 min, 12 secs
60	30	57600/V32/LAPM/V42BIS/7200	57600/V32/LAPM/V42BIS/7200	31 secs

		phase 2 - test 3		
		M/C 1 = Starcomm 14.4k (**Rockwell**)		
		M/C 2 = US Robotics 56k (**USR**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	57600/V32/LAPM/V42BIS/14400	14400/ARQ/V32/LAPM/V42BIS	
20	40	57600/V32/LAPM/V42BIS/14400	14400/ARQ/V32/LAPM/V42BIS	
20	50	57600/V32/LAPM/V42BIS/14400	14400/ARQ/V32/LAPM/V42BIS	
20	55	57600/V32/LAPM/V42BIS/14400	14400/ARQ/V32/LAPM/V42BIS	
20	60	No Connection	No Connection	
20	65	No Connection	No Connection	
30	40	57600/V32/LAPM/V42BIS/14400	14400/ARQ/V32/LAPM/V42BIS	
30	50	57600/V32/LAPM/V42BIS/14400	14400/ARQ/V32/LAPM/V42BIS	
30	55		14400/V32/NONE	GARBAGE
30	60		14400/V32/NONE	GARBAGE
30	65		14400/V32/NONE	GARBAGE
40	20	57600/V32/LAPM/V42BIS/14400	14400/ARQ/V32/LAPM/V42BIS	
40	30	57600/V32/LAPM/V42BIS/14400	14400/ARQ/V32/LAPM/V42BIS	
40	40	57600/V32/LAPM/V42BIS/14400	14400/ARQ/V32/LAPM/V42BIS	
40	50	57600/V32/LAPM/V42BIS/14400	14400/ARQ/V32/LAPM/V42BIS	
40	55	57600/V32/LAPM/V42BIS/14400	14400/ARQ/V32/LAPM/V42BIS	
40	60		14400/V32/NONE	GARBAGE
50	30	57600/V32/LAPM/V42BIS/12000	12000/ARQ/V32/LAPM/V42BIS	
50	40	57600/V32/LAPM/V42BIS/12000	14400/ARQ/V32/LAPM/V42BIS	24 secs
50	45	57600/V32/LAPM/V42BIS/12000	14400/ARQ/V32/LAPM/V42BIS	27 secs
50	50	57600/V32/LAPM/V42BIS/12000	14400/ARQ/V32/LAPM/V42BIS	22 secs
50	55	57600/V32/LAPM/V42BIS/12000	14400/ARQ/V32/LAPM/V42BIS	16 secs
50	60		12000/V32/NONE	GARBAGE
60	20	57600/V32/LAPM/V42BIS/4800	4800/ARQ/V32/LAPM/V42BIS	
60	30	57600/V32/LAPM/V42BIS/4800	4800/ARQ/V32/LAPM/V42BIS	
60	40	57600/V32/LAPM/V42BIS/4800	4800/ARQ/V32/LAPM/V42BIS	
60	50	57600/V32/LAPM/V42BIS/4800	4800/ARQ/V32/LAPM/V42BIS	
60	60	57600/V32/LAPM/V42BIS/4800	4800/ARQ/V32/LAPM/V42BIS	

		phase 2 - test 4		
		M/C 1 = Starvomm 14.4k (Rockwell)		
		M/C 1 = Zoom 56k (Lucent)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	57600/V32/LAPM/V42BIS/14400	14400/V42bis/V32	
20	40	57600/V32/LAPM/V42BIS/14400	14400/V42bis/V32	
20	50	57600/V32/LAPM/V42BIS/14400	14400/V42bis/V32	
20	55	57600/V32/LAPM/V42BIS/12000	12000/V42bis/V32	
20	60	57600/V32/LAPM/V42BIS/9600	9600/V42bis/V32	
20	65	57600/V32/LAPM/V42BIS/4800	4800/V42bis/V22	
30	40	57600/V32/LAPM/V42BIS/14400	14400/V42bis/V32	
30	50	57600/V32/LAPM/V42BIS/14400	14400/V42bis/V32	
30	55	57600/V32/LAPM/V42BIS/12000	12000/V42bis/V32	
30	60	57600/V32/LAPM/V42BIS/7200	7200/V42bis/V32	
30	65	57600/V32/LAPM/V42BIS/4800	4800/V42bis/V32	
40	20	57600/V32/LAPM/V42BIS/14400	14400/V42bis/V32	
40	30	57600/V32/LAPM/V42BIS/14400	14400/V42bis/V32	
40	40	57600/V32/LAPM/V42BIS/14400	14400/V42bis/V32	
40	50	57600/V32/LAPM/V42BIS/14400	14400/V42bis/V32	
40	55	57600/V32/LAPM/V42BIS/12000	12000/V42bis/V32	54 sec
40	60	57600/V32/LAPM/V42BIS/9600	9600/V42bis/V32	12 sec
50	40	57600/V32/LAPM/V42BIS/14400	14400/V42bis/V32	
50	45	57600/V32/LAPM/V42BIS/12000	12000/V42bis/V32	
50	50	57600/V32/LAPM/V42BIS/12000	12000/V42bis/V32	
50	55	57600/V32/LAPM/V42BIS/12000	12000/V42bis/V32	
50	60	57600/V32/LAPM/V42BIS/9600	9600/V42bis/V32	10 sec
50	65	57600/V32/LAPM/V42BIS/4800	4800/V42bis/V32	27 sec
60	20		Connection	GARBAGE

		phase 2 - test 5		
		M/C 1 = Starcomm 14.4k (**Rockwell**)		
		M/C 2 = Best Data 56k (**Conexant**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B	
20	40	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B	
20	50	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B	
20	55	57600/V32/LAPM/V42BIS/14400	12000/V32B/LAPM/V42B	
20	60	57600/V32/LAPM/V42BIS/14400	4800/V32B/LAPM/V42B	
20	65	57600/V32/LAPM/V42BIS/14400	4800/V32B/LAPM/V42B	
20	70	57600/v32/NONE	B103/300/NONE	
20	75	No Connection	No Connection	
30	40	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B	
30	50	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B	
30	55	57600/V32/LAPM/V42BIS/12000	12000/V32B/LAPM/V42B	
30	60	57600/V32/LAPM/V42BIS/4800	4800/V32B/LAPM/V42B	
30	65	57600/V32/LAPM/V42BIS/4800	4800/V32B/LAPM/V42B	
30	70	No Connection	No Connection	
40	20	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B	
40	30	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B	
40	40	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B	
40	50	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B	
40	55	57600/V32/LAPM/V42BIS/12000	12000/V32B/LAPM/V42B	
40	60	57600/V32/LAPM/V42BIS/4800	4800/V32B/LAPM/V42B	
40	65	57600/V32/LAPM/V42BIS/4800	4800/V32B/LAPM/V42B	
40	70	No Connection	No Connection	
50	40	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B	
50	45	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B	
50	50	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B	
50	55	57600/V32/LAPM/V42BIS/12000	12000/V32B/LAPM/V42B	
50	60	57600/V32/LAPM/V42BIS/4800	4800/V32B/LAPM/V42B	
50	65	No Connection	No Connection	
60	20	57600/v32/NONE	B103/300/NONE	
60	30	57600/v32/NONE	B103/300/NONE	
60	40	57600/v32/NONE	B103/300/NONE	
60	45	57600/v32/NONE	B103/300/NONE	20 sec

		phase 2 - test 6		
		M/C 1 = US Robotics (**USR**)		
		M/C 2 = Best Data 56k (**Conexant**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	33600/ARQ/V34/LAPM/V42BIS	33600/V32B/LAPM/V42B	
20	40	33600/ARQ/V34/LAPM/V42BIS	28800/V32B/LAPM/V42B	
20	50	33600/ARQ/V34/LAPM/V42BIS	16800/V32B/LAPM/V42B	
20	55	33600/ARQ/V34/LAPM/V42BIS	7200/V32B/LAPM/V42B	
20	60	21600/ARQ/V34/LAPM/V42BIS	4800/V32B/LAPM/V42B	
20	65	No Connection	No Connection	
30	40	33600/ARQ/V34/LAPM/V42BIS	28800/V32B/LAPM/V42B	
30	50	33600/ARQ/V34/LAPM/V42BIS	16800/V32B/LAPM/V42B	
30	55	33600/ARQ/V34/LAPM/V42BIS	7200/V32B/LAPM/V42B	
30	60	21600/ARQ/V34/LAPM/V42BIS	4800/V32B/LAPM/V42B	
30	65	No Connection	No Connection	
30	70	31200/ARQ/V34/LAPM/V42BIS	33600/V32B/LAPM/V42B	
40	20	31200/ARQ/V34/LAPM/V42BIS	33600/V32B/LAPM/V42B	strange
40	30	31200/ARQ/V34/LAPM/V42BIS	26400/V32B/LAPM/V42B	
40	40	31200/ARQ/V34/LAPM/V42BIS	16800/V32B/LAPM/V42B	
40	50	31200/ARQ/V34/LAPM/V42BIS	16800/V32B/LAPM/V42B	
40	55	31200/ARQ/V34/LAPM/V42BIS	7200/V32B/LAPM/V42B	
40	60	19200/ARQ/V34/LAPM/V42BIS	4800/V32B/LAPM/V42B	
40	65	No Connection	No Connection	
50	20	21600/ARQ/V34/LAPM/V42BIS	33600/V32B/LAPM/V42B	
50	30	21600/ARQ/V34/LAPM/V42BIS	33600/V32B/LAPM/V42B	
50	40	21600/ARQ/V34/LAPM/V42BIS	26400/V32B/LAPM/V42B	
50	45	21600/ARQ/V34/LAPM/V42BIS	21600/V32B/LAPM/V42B	
50	50	21600/ARQ/V34/LAPM/V42BIS	16800/V32B/LAPM/V42B	
50	55	21600/ARQ/V34/LAPM/V42BIS	7200/V32B/LAPM/V42B	
50	60	14400/ARQ/V34/LAPM/V42BIS	4800/V32B/LAPM/V42B	
50	65	No Connection	No Connection	
60	20	9600/ARQ/V34/LAPM/V42BIS	24000/V32B/LAPM/V42B	
60	30	9600/ARQ/V34/LAPM/V42BIS	24000/V32B/LAPM/V42B	
60	40	9600/ARQ/V34/LAPM/V42BIS	21600/V32B/LAPM/V42B	
60	45	9600/ARQ/V34/LAPM/V42BIS	19200/V32B/LAPM/V42B	
60	50	9600/ARQ/V34/LAPM/V42BIS	14400/V32B/LAPM/V42B	
60	55	9600/ARQ/V34/LAPM/V42BIS	7200/V32B/LAPM/V42B	
60	60	7200/ARQ/V34/LAPM/V42BIS	4800/V32B/LAPM/V42B	
60	65	No Connection	No Connection	

		phase 2 - test 7		
		M/C 1 = US Robotics (**USR**)		
		M/C 2 = Zoom 56 k (**Lucent**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	33600/ARQ/V34/LAPM/V42BIS	33600/V42bis	
20	40	33600/ARQ/V34/LAPM/V42BIS	28800/V42bis	
20	50	33600/ARQ/V34/LAPM/V42BIS	19200/V42bis	
20	55	33600/ARQ/V34/LAPM/V42BIS	14400/V42bis	
20	60	28800/ARQ/V34/LAPM/V42BIS	4800/V42bis	
20	65	21600/ARQ/V34/LAPM/V42BIS	4800/V42bis	
20	70	No Connection	No Connection	
30	40	33600/ARQ/V34/LAPM/V42BIS	14400/V42bis	
30	50	33600/ARQ/V34/LAPM/V42BIS	14400/V42bis	
30	55	31200/ARQ/V34/LAPM/V42BIS	14400/V42bis	
30	60	26400/ARQ/V34/LAPM/V42BIS	4800/V42bis	
30	65	21600/ARQ/V34/LAPM/V42BIS	7200/V42bis	
30	70	No Connection	No Connection	
40	20	28800/ARQ/V34/LAPM/V42BIS	33600/V42bis	
40	30	28800/ARQ/V34/LAPM/V42BIS	33600/V42bis	
40	40	28800/ARQ/V34/LAPM/V42BIS	31200/V42bis	
40	50	28800/ARQ/V34/LAPM/V42BIS	19200/V42bis	
40	55	28800/ARQ/V34/LAPM/V42BIS	14400/V42bis	
40	60	28800/ARQ/V34/LAPM/V42BIS	4800/V42bis	
40	65	21600/ARQ/V34/LAPM/V42BIS	7200/V42bis	30 secs
50	30	19200/ARQ/V34/LAPM/V42BIS	33600/V42bis	
50	40	19200/ARQ/V34/LAPM/V42BIS	28800/V42bis	
50	45	19200/ARQ/V34/LAPM/V42BIS	24000/V42bis	
50	50	19200/ARQ/V34/LAPM/V42BIS	19200/V42bis	
50	55	19200/ARQ/V34/LAPM/V42BIS	14400/V42bis	
50	60	16800/ARQ/V34/LAPM/V42BIS	4800/V42bis	
50	65	16800/ARQ/V34/LAPM/V42BIS	4800/V42bis	
50	70	No Connection	No Connection	
60	20	7200/ARQ/V34/LAPM/V42BIS	26400/V42bis	
60	30	7200/ARQ/V34/LAPM/V42BIS	26400/V42bis	
60	40	7200/ARQ/V34/LAPM/V42BIS	24000/V42bis	
60	45	7200/ARQ/V34/LAPM/V42BIS	21600/V42bis	
60	50	7200/ARQ/V34/LAPM/V42BIS	19200/V42bis	
60	60	7200/ARQ/V34/LAPM/V42BIS	4800/V42bis	
60	65	7200/V34/NONE	4800/NoEC	Garbage

		phase 2 - test 8		
		M/C 1 = Zoom 56 k (**Lucent**)		
		M/C 2 = Best Data 56 k (**Conexant**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	33600/V42bis	33600/V34/LAPM/V42B	
20	40	33600/V42bis	26400/V34/LAPM/V42B	
20	50	33600/V42bis	14400/V34/LAPM/V42B	
20	55	33600/V42bis	7200/V34/LAPM/V42B	
20	60	21600/V42bis	2400/V34/LAPM/V42B	
20	65	No Connection	No Connection	
30	40	33600/V42bis	26400/V34/LAPM/V42B	
30	50	33600/V42bis	14400/V34/LAPM/V42B	
30	55	33600/V42bis	7200/V34/LAPM/V42B	
30	60	21600/V42bis	2400/V34/LAPM/V42B	
30	65	No Connection	No Connection	
40	20	31200/V42bis	33600/V34/LAPM/V42B	
40	30	31200/V42bis	33600/V34/LAPM/V42B	
40	40	31200/V42bis	26400/V34/LAPM/V42B	
40	50	31200/V42bis	14400/V34/LAPM/V42B	
40	55	28000/V42bis	7200/V34/LAPM/V42B	
40	60	21600/V42bis	2400/V34/LAPM/V42B	
40	65	No Connection	No Connection	
50	40	21600/V42bis	26400/V34/LAPM/V42B	
50	45	21600/V42bis	21600/V34/LAPM/V42B	
50	50	21600/V42bis	14400/V34/LAPM/V42B	
50	55	21600/V42bis	7200/V34/LAPM/V42B	
50	60	16800/V42bis	2400/V34/LAPM/V42B	
50	65	No Connection	No Connection	
60	20	9600/V42bis	24000/V34/LAPM/V42B	
60	30	9600/V42bis	26400/V34/LAPM/V42B	
60	40	9600/V42bis	24000/V34/LAPM/V42B	
60	45	9600/V42bis	19200/V34/LAPM/V42B	
60	50	9600/V42bis	14400/V34/LAPM/V42B	
60	55	9600/V42bis	7200/V34/LAPM/V42B	
60	60	7200/V42bis	2400/V34/LAPM/V42B	
60	65	No Connection	No Connection	

		phase 2 - test 9		
		M/C 1 = Starrcomm 14.4 (**Rockwell**)		
		M/C 2 = Cascade (**Rockwell**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	50	57600/V32/LAPM/NONE/14400	14400/V32B/LAPM/NONE/ARQ	
20	55	57600/V32/LAPM/NONE/12000	12000/V32B/LAPM/NONE/ARQ	
20	60	57600/V32/LAPM/NONE/4800	4800/V32B/LAPM/NONE/ARQ	
20	65	57600/V32/LAPM/NONE/4800	4800/V32B/LAPM/NONE/ARQ	
20	70	No Connection	No Connection	
30	50	57600/V32/LAPM/NONE/14400	14400/V32B/LAPM/NONE/ARQ	
30	55	57600/V32/LAPM/NONE/12000	12000/V32B/LAPM/NONE/ARQ	
30	60	57600/V32/LAPM/NONE/4800	4800/V32B/LAPM/NONE/ARQ	
30	65	57600/V32/LAPM/NONE/4800	4800/V32B/LAPM/NONE/ARQ	
30	70	No Connection	No Connection	
40	50	57600/V32/LAPM/NONE/14400	14400/V32B/LAPM/NONE/ARQ	
40	55	57600/V32/LAPM/NONE/12000	12000/V32B/LAPM/NONE/ARQ	
40	60	57600/V32/LAPM/NONE/4800	4800/V32B/LAPM/NONE/ARQ	
40	65	57600/V32/LAPM/NONE/4800	4800/V32B/LAPM/NONE/ARQ	
40	70	No Connection	No Connection	
50	50	57600/V32/LAPM/NONE/14400	14400/V32B/LAPM/NONE/ARQ	
50	55	57600/V32/LAPM/NONE/12000	12000/V32B/LAPM/NONE/ARQ	
50	60	57600/V32/LAPM/NONE/4800	4800/V32B/LAPM/NONE/ARQ	
50	65	57600/V32/LAPM/NONE/4800	4800/V32B/LAPM/NONE/ARQ	
50	70	No Connection	No Connection	
60	20	57600/V32/LAPM/NONE/7200		31 secs
60	30	57600/V32/LAPM/NONE/7200		20 secs
60	40	57600/B103/NONE/300	B103/300/NONE	

		phase 2 - test 10		
		M/C 1 = Zoom 56 k (**Lucent**)		
		M/C 2 = Cascade (**Rockwell**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	50	14000/V42	14400/V32B/LAPM/NONE/ARQ	
20	55	9600/V42	9600/V32B/LAPM/NONE/ARQ	
20	60	No Connection	No Connection	
30	50	14000/V42	14400/V32B/LAPM/NONE/ARQ	
30	55	9600/V42	12000/V32B/LAPM/NONE/ARQ	
30	60	No Connection	No Connection	
40	50	14000/V42	14400/V32B/LAPM/NONE/ARQ	
40	55	9600/V42	12000/V32B/LAPM/NONE/ARQ	
40	60	No Connection	No Connection	
50	40	14000/V42	14400/V32B/LAPM/NONE/ARQ	
50	45	12000/V42	12000/V32B/LAPM/NONE/ARQ	
50	50	12000/V42	12000/V32B/LAPM/NONE/ARQ	
50	55	9600/V42	9600/V32B/LAPM/NONE/ARQ	
50	60	No Connection	No Connection	
60	20	4800/V42	4800/V32B/LAPM/NONE/ARQ	
60	30	4800/V42	4800/V32B/LAPM/NONE/ARQ	36 secs
60	40	4800/V42	4800/V32B/LAPM/NONE/ARQ	37 secs
60	50	4800/V42	4800/V32B/LAPM/NONE/ARQ	36 secs
60	60	No Connection	No Connection	

		phase 2 - test 11		
		M/C 1 = US Robotics 56 k (**USR**)		
		M/C 2 = Cascade (**Rockwell**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	50	14400/ARQ/V32/LAPM	14400/V32B/LAPM/NONE/ARQ	
20	55	12000/ARQ/V32/LAPM	12000/V32B/LAPM/NONE/ARQ	
20	60	4800/ARQ/V32/LAPM	4800/V32B/LAPM/NONE/ARQ	8 secs
20	65	No Connection	No Connection	
30	50	14400/ARQ/V32/LAPM	14400/V32B/LAPM/NONE/ARQ	
30	55	12000/ARQ/V32/LAPM	12000/V32B/LAPM/NONE/ARQ	8 secs
30	60	4800/ARQ/V32/LAPM	4800/V32B/LAPM/NONE/ARQ	8 secs
30	65	No Connection	No Connection	
40	50	14400/ARQ/V32/LAPM	14400/V32B/LAPM/NONE/ARQ	
40	55	4800/ARQ/V32/LAPM	4800/V32B/LAPM/NONE/ARQ	8 secs
40	60	4800/ARQ/V32/LAPM	4800/V32B/LAPM/NONE/ARQ	8 secs
40	65	No Connection	No Connection	
50	50	14400/ARQ/V32/LAPM	14400/V32B/LAPM/NONE/ARQ	
50	55	12000/ARQ/V32/LAPM	12000/V32B/LAPM/NONE/ARQ	8 secs
50	60	12000/ARQ/V32/LAPM	12000/V32B/LAPM/NONE/ARQ	8 secs
50	65	No Connection	No Connection	
60	20	14400/ARQ/V32/LAPM	14400/V32B/LAPM/NONE/ARQ	Garbage
60	30	14400/ARQ/V32/LAPM	14400/V32B/LAPM/NONE/ARQ	Garbage
60	40	14400/V32/NONE	No Connection	Garbage

		phase 2 - **test 12**		
		M/C 1 =Best Data 56 k (**Conexant**)		
		M/C 2 = Cascade (**Rockwell**)		
Line 1	**Line 3**	**M/C 1** - **line1**	**M/C 2** - **line 3**	**Comment**
20	50	14400/V32B/LAPM/NONE/ARQ	14400/V32B/LAPM/NONE/ARQ	
20	55	12000/V32B/LAPM/NONE/ARQ	12000/V32B/LAPM/NONE/ARQ	
20	60	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
20	65	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
20	70	No Connection	No Connection	
30	50	14400/V32B/LAPM/NONE/ARQ	14400/V32B/LAPM/NONE/ARQ	
30	55	12000/V32B/LAPM/NONE/ARQ	12000/V32B/LAPM/NONE/ARQ	
30	60	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
30	65	No Connection	No Connection	
40	50	14400/V32B/LAPM/NONE/ARQ	14400/V32B/LAPM/NONE/ARQ	
40	55	14400/V32B/LAPM/NONE/ARQ	14400/V32B/LAPM/NONE/ARQ	
40	60	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
40	65	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	1 min:12 secs
40	70	No Connection	No Connection	
50	50	14400/V32B/LAPM/NONE/ARQ	14400/V32B/LAPM/NONE/ARQ	
50	55	12000/V32B/LAPM/NONE/ARQ	12000/V32B/LAPM/NONE/ARQ	
50	60	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
50	65	No Connection	No Connection	
60	20	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
60	30	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
60	40	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
60	50	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
60	60	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
60	60	No Connection	No Connection	

		phase 2 - test 13		
		M/C 1 = Cascade 33.6 k (**Rockwell**)		
		M/C 2 = Cascade 14.4 k (**Rockwell**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	50	14400/V32B/LAPM/NONE/ARQ	14400/V32B/LAPM/NONE/ARQ	
20	55	12000/V32B/LAPM/NONE/ARQ	12000/V32B/LAPM/NONE/ARQ	
20	60	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
20	65	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
20	70	No Connection	No Connection	
30	50	14400/V32B/LAPM/NONE/ARQ	14400/V32B/LAPM/NONE/ARQ	
30	55	12000/V32B/LAPM/NONE/ARQ	12000/V32B/LAPM/NONE/ARQ	
30	60	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
30	65	No Connection	No Connection	
40	50	14400/V32B/LAPM/NONE/ARQ	14400/V32B/LAPM/NONE/ARQ	
40	55	12000/V32B/LAPM/NONE/ARQ	14400/V32B/LAPM/NONE/ARQ	
40	60	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
40	65	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	1 min:12 secs
40	70	No Connection	No Connection	
50	50	14400/V32B/LAPM/NONE/ARQ	14400/V32B/LAPM/NONE/ARQ	
50	55	12000/V32B/LAPM/NONE/ARQ	12000/V32B/LAPM/NONE/ARQ	
50	60	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
50	65	No Connection	No Connection	
50	70	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
60	20	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
60	30	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
60	40	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
60	50	4800/V32B/LAPM/NONE/ARQ	4800/V32B/LAPM/NONE/ARQ	
60	60	No Connection	No Connection	

		phase 2 - test 14		
		M/C 1 = Laptop 56 k (**Lucent**)		
		M/C 2 = Cascade 14.4 k (**Rockwell**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	50	14400/V42	14400/V32B/LAPM/NONE/ARQ	
20	55	9600/V42	9600/V32B/LAPM/NONE/ARQ	
20	60	4800/V42	4800/V32B/LAPM/NONE/ARQ	
20	65	No Connection	No Connection	
30	50	14400/V42	14400/V32B/LAPM/NONE/ARQ	
30	55	9600/V42	9600/V32B/LAPM/NONE/ARQ	
30	60	4800/V42	4800/V32B/LAPM/NONE/ARQ	
30	65	No Connection	No Connection	
40	50	14400/V42	14400/V32B/LAPM/NONE/ARQ	
40	55	9600/V42	9600/V32B/LAPM/NONE/ARQ	
40	60	4800/V42	4800/V32B/LAPM/NONE/ARQ	
40	65	No Connection	No Connection	
50	50	14400/V42	14400/V32B/LAPM/NONE/ARQ	
50	55	9600/V42	9600/V32B/LAPM/NONE/ARQ	
50	60	4800/V42	4800/V32B/LAPM/NONE/ARQ	
50	65	No Connection	No Connection	
60	20	4800/V42	4800/V32B/LAPM/NONE/ARQ	
60	30	4800/V42	4800/V32B/LAPM/NONE/ARQ	
60	40	4800/V42	4800/V32B/LAPM/NONE/ARQ	
60	50	4800/V42	4800/V32B/LAPM/NONE/ARQ	
60	60	4800/V42	4800/V32B/LAPM/NONE/ARQ	
60	65	No Connection		

		phase 2 - test 15		
		M/C 1 = Laptop56 k (**Lucent**)		
		M/C 2 = Cascade 33.6k (**Rockwell**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	33600/V42	33600/V34/LAPM/NONE/ARQ	
20	30	33600/V42	33600/V34/LAPM/NONE/ARQ	
20	40	33600/V42	26400/V34/LAPM/NONE/ARQ	
20	50	33600/V42	16800/V34/LAPM/NONE/ARQ	
20	55	31200/V42	9600/V34/LAPM/NONE/ARQ	
20	60	21600/V42	2400/V34/LAPM/NONE/ARQ	
20	65	NO CONNECTION	NO CONNECTION	
30	30	33600/V42	33600/V34/LAPM/NONE/ARQ	
30	40	33600/V42	26400/V34/LAPM/NONE/ARQ	
30	50	33600/V42	16800/V34/LAPM/NONE/ARQ	
30	55	31200/V42	9600/V34/LAPM/NONE/ARQ	
30	60	21600/V42	4800/V34/LAPM/NONE/ARQ	
30	65	NO CONNECTION	NO CONNECTION	
40	20	26400/V42	33600/V34/LAPM/NONE/ARQ	
40	30	26400/V42	31200/V34/LAPM/NONE/ARQ	
40	40	26400/V42	26400/V34/LAPM/NONE/ARQ	
40	50	26400/V42	16800/V34/LAPM/NONE/ARQ	
40	55	26400/V42	9600/V34/LAPM/NONE/ARQ	
40	60	21600/V42	4800/V34/LAPM/NONE/ARQ	
40	65	21600/V42	4800/V34/LAPM/NONE/ARQ	
40	70	NO CONNECTION	NO CONNECTION	
50	50	16800/V42	16800/V34/LAPM/NONE/ARQ	
50	60	12000/V42	4800/V34/LAPM/NONE/ARQ	
50	65	NO CONNECTION	NO CONNECTION	
60	40	4800/V42	21600/V34/LAPM/NONE/ARQ	
60	50	4800/V42	14400/V34/LAPM/NONE/ARQ	
60	60	4800/V42	4800/V34/LAPM/NONE/ARQ	
60	65	NO CONNECTION	NO CONNECTION	

		phase 2 - test 16		
		M/C 1 = Starcomm 14.4 k (**Rockwell**)		
		M/C 2 = Cascade 33.6k (**Rockwell**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	50	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B/ARQ	
20	55	57600/V32/LAPM/V42BIS/12000	12000/V32B/LAPM/V42B/ARQ	
20	60	57600/V32/LAPM/V42BIS/4800	4800/V32/LAPM/V42B/ARQ	
20	65	57600/V32/LAPM/V42BIS/4800	4800/V32/LAPM/V42B/ARQ	
20	70	NO CONNECTION	NO CONNECTION	
30	50	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B/ARQ	
30	55	57600/V32/LAPM/V42BIS/12000	12000/V32B/LAPM/V42B/ARQ	
30	60	57600/V32/LAPM/V42BIS/4800	4800/V32/LAPM/V42B/ARQ	
30	65	57600/V32/LAPM/V42BIS/4800	4800/V32/LAPM/V42B/ARQ	
30	70	NO CONNECTION	NO CONNECTION	
40	50	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B/ARQ	
40	55	57600/V32/LAPM/V42BIS/12000	12000/V32B/LAPM/V42B/ARQ	
40	60	57600/V32/LAPM/V42BIS/4800	4800/V32/LAPM/V42B/ARQ	
40	65	57600/V32/LAPM/V42BIS/4800	4800/V32/LAPM/V42B/ARQ	
40	70	NO CONNECTION	NO CONNECTION	
50	50	57600/V32/LAPM/V42BIS/14400	14400/V32B/LAPM/V42B/ARQ	
50	55	57600/V32/LAPM/V42BIS/12000	12000/V32B/LAPM/V42B/ARQ	
50	60	57600/V32/LAPM/V42BIS/4800	4800/V32/LAPM/V42B/ARQ	
50	65	57600/V32/LAPM/V42BIS/4800	4800/V32/LAPM/V42B/ARQ	
50	70	NO CONNECTION	NO CONNECTION	
60	20	B103/300/None	B103/300/NONE	16 secs

		phase 2 - test 17		
		M/C 1 = BestData 56k (**Conexant**)		
		M/C 2 = Cascade 33.6k (**Rockwell**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	33600/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
20	30	33600/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
20	40	33600/V34/LAPM/V42BIS	28800/V34/LAPM/V42B/ARQ	
20	50	33600/V34/LAPM/V42BIS	19200/V34/LAPM/V42B/ARQ	
20	55	33600/V34/LAPM/V42BIS	9600/V34/LAPM/V42B/ARQ	
20	60	31200/V34/LAPM/V42BIS	4800/V34/LAPM/V42B/ARQ	
20	65	NO CONNECTION	NO CONNECTION	
30	20	33600/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
30	30	33600/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
30	40	33600/V34/LAPM/V42BIS	28800/V34/LAPM/V42B/ARQ	
30	50	33600/V34/LAPM/V42BIS	16800/V34/LAPM/V42B/ARQ	
30	55	33600/V34/LAPM/V42BIS	9600/V34/LAPM/V42B/ARQ	
30	60	26400/V34/LAPM/V42BIS	4800/V34/LAPM/V42B/ARQ	
30	65	NO CONNECTION	NO CONNECTION	
40	20	28800/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
40	30	28800/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
40	40	26400/V34/LAPM/V42BIS	28800/V34/LAPM/V42B/ARQ	
40	50	28800/V34/LAPM/V42BIS	19200/V34/LAPM/V42B/ARQ	
40	55	26400/V34/LAPM/V42BIS	12000/V34/LAPM/V42B/ARQ	
40	60	24000/V34/LAPM/V42BIS	4800/V34/LAPM/V42B/ARQ	
40	65	19200/V34/LAPM/V42BIS	2400/V34/LAPM/V42B/ARQ	1 min, 29 secs
50	20	16800/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
50	30	16800/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
50	40	16800/V34/LAPM/V42BIS	28800/V34/LAPM/V42B/ARQ	
50	50	16800/V34/LAPM/V42BIS	19200/V34/LAPM/V42B/ARQ	
50	55	16800/V34/LAPM/V42BIS	9600/V34/LAPM/V42B/ARQ	
50	60	16800/V34/LAPM/V42BIS	4800/V34/LAPM/V42B/ARQ	
50	65	NO CONNECTION	NO CONNECTION	
60	20	4800/V34/LAPM/V42BIS	21600/V34/LAPM/V42B/ARQ	
60	30	4800/V34/LAPM/V42BIS	21600/V34/LAPM/V42B/ARQ	
60	40	4800/V34/LAPM/V42BIS	19200/V34/LAPM/V42B/ARQ	
60	50	4800/V34/LAPM/V42BIS	12000/V34/LAPM/V42B/ARQ	
60	60	4800/V34/LAPM/V42BIS	4800/V34/LAPM/V42B/ARQ	
60	65	NO CONNECTION	NO CONNECTION	

		phase 2 - test 18		
		M/C 1 = USR 56k (**USR**)		
		M/C 2 = Cascade 33.6k (**Rockwell**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	33600/ARQ/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
20	30	33600/ARQ/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
20	40	33600/ARQ/V34/LAPM/V42BIS	28800/V34/LAPM/V42B/ARQ	
20	50	33600/ARQ/V34/LAPM/V42BIS	16800/V34/LAPM/V42B/ARQ	
20	55	28800/ARQ/V34/LAPM/V42BIS	9600/V34/LAPM/V42B/ARQ	
20	60	21600/ARQ/V34/LAPM/V42BIS	4800/V34/LAPM/V42B/ARQ	
20	65	NO CONNECTION	NO CONNECTION	
30	20	33600/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
30	30	33600/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
30	40	33600/V34/LAPM/V42BIS	28800/V34/LAPM/V42B/ARQ	
30	50	33600/V34/LAPM/V42BIS	16800/V34/LAPM/V42B/ARQ	
30	55	31200/V34/LAPM/V42BIS	9600/V34/LAPM/V42B/ARQ	
30	60	21600/V34/LAPM/V42BIS	4800/V34/LAPM/V42B/ARQ	
30	65	NO CONNECTION	NO CONNECTION	
40	20	28800/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
40	30	28800/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
40	40	28800/V34/LAPM/V42BIS	28800/V34/LAPM/V42B/ARQ	
40	50	28800/V34/LAPM/V42BIS	16800/V34/LAPM/V42B/ARQ	
40	55	28800/V34/LAPM/V42BIS	9600/V34/LAPM/V42B/ARQ	
40	60	28800/V34/LAPM/V42BIS	4800/V34/LAPM/V42B/ARQ	
40	65	NO CONNECTION	NO CONNECTION	
50	20	19200/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
50	30	19200/V34/LAPM/V42BIS	33600/V34/LAPM/V42B/ARQ	
50	40	19200/V34/LAPM/V42BIS	26400/V34/LAPM/V42B/ARQ	
50	50	19200/V34/LAPM/V42BIS	16800/V34/LAPM/V42B/ARQ	
50	55	19200/V34/LAPM/V42BIS	9600/V34/LAPM/V42B/ARQ	
50	60	14400/V34/LAPM/V42BIS	4800/V34/LAPM/V42B/ARQ	
50	65	NO CONNECTION	NO CONNECTION	
60	20	9600/V34/LAPM/V42BIS	24000/V34/LAPM/V42B/ARQ	
60	30	7200/V34/LAPM/V42BIS	21600/V34/LAPM/V42B/ARQ	
60	40	9600/V34/LAPM/V42BIS	21600/V34/LAPM/V42B/ARQ	
60	50	7200/V34/LAPM/V42BIS	14400/V34/LAPM/V42B/ARQ	
60	60	7200/V34/LAPM/V42BIS	4800/V34/LAPM/V42B/ARQ	
60	65	NO CONNECTION	NO CONNECTION	

		phase 2 - test 19		
		M/C 1 = Zoom 56k (**Lucent**)		
		M/C 2 = Cascade 33.6k (**Rockwell**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	33600/V42bis	33600/V34/LAPM/V42B/ARQ	
20	30	33600/V42bis	33600/V34/LAPM/V42B/ARQ	
20	40	33600/V42bis	26400/V34/LAPM/V42B/ARQ	
20	50	33600/V42bis	16800/V34/LAPM/V42B/ARQ	
20	55	31200/V42bis	7200/V34/LAPM/V42B/ARQ	
20	60	21600/V42bis	4800/V34/LAPM/V42B/ARQ	
20	65	NO CONNECTION	NO CONNECTION	
30	30	33600/V42bis	33600/V34/LAPM/V42B/ARQ	
30	40	33600/V42bis	26400/V34/LAPM/V42B/ARQ	
30	50	33600/V42bis	16800/V34/LAPM/V42B/ARQ	
30	55	31200/V42bis	7200/V34/LAPM/V42B/ARQ	
30	60	NO CONNECTION	NO CONNECTION	
40	30	31200/V42bis	33600/V34/LAPM/V42B/ARQ	
40	40	31200/V42bis	26400/V34/LAPM/V42B/ARQ	
40	50	28800/V42bis	14400/V34/LAPM/V42B/ARQ	
40	55	28800/V42bis	9600/V34/LAPM/V42B/ARQ	
40	60	21600/V42bis	4800/V34/LAPM/V42B/ARQ	
40	65	NO CONNECTION	NO CONNECTION	
50	30	19200/V42bis	33600/V34/LAPM/V42B/ARQ	
50	40	19200/V42bis	26400/V34/LAPM/V42B/ARQ	
50	50	19200/V42bis	16800/V34/LAPM/V42B/ARQ	
50	55	19200/V42bis	7200/V34/LAPM/V42B/ARQ	
50	60	NO CONNECTION	NO CONNECTION	
60	20	4800/V42bis	24000/V34/LAPM/V42B/ARQ	
60	30	4800/V42bis	24000/V34/LAPM/V42B/ARQ	
60	40	7200/V42bis	24000/V34/LAPM/V42B/ARQ	
60	50	4800/V42bis	14400/V34/LAPM/V42B/ARQ	
60	60	NO CONNECTION	NO CONNECTION	

		phase 2 - test 20		
		M/C 1 = Zoom 56k (**Lucent**)		
		M/C 2 = Laptop 56k (**Lucent**)		
Line 1	**Line 3**	**M/C 1 - line1**	**M/C 2 - line 3**	**Comment**
20	20	33600/V42bis	33600/V34/LAPM/V42B	
20	30	33600/V42bis	33600/V34/LAPM/V42B	
20	40	33600/V42bis	28800/V34/LAPM/V42B	
20	50	33600/V42bis	16800/V34/LAPM/V42B	
20	55	26400/V42bis	12000/V34/LAPM/V42B	
20	60	21600/V42bis	4800/V34/LAPM/V42B	
20	65	19200/V42bis	4800/V34/LAPM/V42B	
20	70	NO CONNECTION	NO CONNECTION	
30	30	33600/V42bis	33600/V34/LAPM/V42B/	
30	40	33600/V42bis	28800/V34/LAPM/V42B	
30	50	33600/V42bis	19200/V34/LAPM/V42B	
30	55	31200/V42bis	12000/V34/LAPM/V42B	
30	60	21600/V42bis	7200/V34/LAPM/V42B	
30	65	NO CONNECTION	NO CONNECTION	
40	30	31200/V42bis	33600/V34/LAPM/V42B/	
40	40	31200/V42bis	28800/V34/LAPM/V42B	
40	50	28800/V42bis	19200/V34/LAPM/V42B	
40	55	28800/V42bis	12000/V34/LAPM/V42B	
40	60	21600/V42bis	7200/V34/LAPM/V42B	
40	65	16800/V42bis	4800/V34/LAPM/V42B	
40	70	NO CONNECTION	NO CONNECTION	
50	30	19200/V42bis	33600/V34/LAPM/V42B/	
50	40	16800/V42bis	26400/V34/LAPM/V42B/	
50	50	16800/V42bis	16800/V34/LAPM/V42B/	
50	55	16800/V42bis	12000/V34/LAPM/V42B	
50	60	16800/V42bis	4800/V34/LAPM/V42B	
50	65	14400/V42bis	4800/V34/LAPM/V42B	
50	70	NO CONNECTION	NO CONNECTION	
60	20	4800/V42bis	28800/V34/LAPM/V42B	
60	30	4800/V42bis	28800/V34/LAPM/V42B	
60	40	7200/V42bis	26400/V34/LAPM/V42B/	
60	50	4800/V42bis	16800/V34/LAPM/V42B/	
60	60	4800/V42bis	4800/V34/LAPM/V42B	
60	65	4800/V42bis	4800/V34/LAPM/V42B	
60	70	NO CONNECTION	NO CONNECTION	

C.3. Phase III Tests

In the following tests the attenuation was applied equally in each communication direction. The noise level was increased until the connection could not be achieved or maintained. In the early tests the telephone lines signal level and quality were recorded for each attenuation setting. These tests are listed below. In the remaining combinations of modems, the attenuation level was varied and only the maximum attenuation level for reliable connection was recorded. The results of the attenuation tests are summarized in Table 4 in Section 3.3. In addition, some tests were conducted with attenuation on the calling modem fixed at 28 dB while the attenuation on the answering modems was varied. The results of these tests are summarized in Table 5 in Section 3.3.

Test # 1:

Machine 1: Starcomm 14.4 modem (recognized as Starcomm)
Machine 2: Win Lucent Modem 56k (Internal – Laptop modem)

Chipset on Starcomm 14.4 modem was Rockwell 93
Chipset on Laptop modem was Lucent

Teltone Parameters: Impedance = 900Ω, Loop Current = 35mA

Attn (dB)	M/C # 1	M/C # 2	Line Signal Level	Line Signal Quality
4	19200 / V32 / LAPM/ V.42bis / 14400	14400 / V.42bis	17	6
26	19200 / V32 / LAPM/ V.42bis / 14400	14400 / V.42bis	27	7
27	19200 / V32 / LAPM/ V.42bis / 14400	14400 / V.42bis	35	11
28	19200 / V32 / LAPM/ V.42bis / 14400	14400 / V.42bis	36	15
29	19200 / V32 / LAPM/ V.42bis / 14400	14400 / V.42bis	36	13-18
30	19200 / V32 / LAPM/ V.42bis / 14400	14400 / V.42bis	38	19-23
31	19200 / V32 / LAPM/ V.42bis / 14400	14400 / V.42bis	39	17-24
29	19200 / V32 / LAPM/ V.42bis / 14400	14400 / V.42bis	41	21-43
30	19200 / V32 / LAPM/ V.42bis / 14400	14400 / V.42bis	42	19-85

Got disconnected at 30 dB attenuation

In this test and all others to follow it should be noted that the line signal level and line signal quality of the telephone line was checked by the Rockwell chipset commands.

The command used for Line Signal Level is: AT%L

The command used for Line Signal Quality is: AT%Q

Test # 2:

Machine 1: Starcomm 14.4 modem
Machine 2: Starcomm 14.4 Modem

Chipset on Machine # 1 was Rockwell 93
Chipset on Machine # 2 was Rockwell 94

Teltone Parameters: Impedance = 900Ω, Loop Current = 35mA

Attn (dB)	M/C # 1	M/C # 2	Line Signal Level	Line Signal Quality
4	57600 / V32 / LAPM/ V.42bis / 14400	Same	15	6--8
14	57600 / V32 / LAPM/ V.42bis / 14400	Same	26	6--8
24	57600 / V32 / LAPM/ V.42bis / 14400	Same	35	11--13
25	57600 / V32 / LAPM/ V.42bis / 14400	Same	36	12--14
26	57600 / V32 / LAPM/ V.42bis / 14400	Same	38	13--15
28	57600 / V32 / LAPM/ V.42bis / 14400	Same	39	15--23
30	57600 / V32 / LAPM/ V.42bis / 14400	Same	41	22--26
32	57600 / V32 / LAPM/ V.42bis / 14400	Same	44	0--120

At 32 dB, the connection was lost after 1 minute and 25 seconds.

Test # 3:

Machine 1: Starcomm 14.4 modem
Machine 2: USR 56 k V.90

Chipset on Machine # 1 was Rockwell 93
Chipset on Machine # 2 was US Robotics

Teltone Parameters: Impedance = 900Ω, Loop Current = 35mA

Attn (dB)	M/C # 1	M/C # 2	Signal Level	Signal Quality
4	57600 / V32 / LAPM/ V.42bis / 14400	14000/ARQ/V/32/LAPM/V42bis	17	5--8
14	57600 / V32 / LAPM/ V.42bis / 14400	Same	27	5--7
24	57600 / V32 / LAPM/ V.42bis / 14400	Same	36	10--14
25	57600 / V32 / LAPM/ V.42bis / 14400	Same	38	11--22
26	57600 / V32 / LAPM/ V.42bis / 14400	Same	38	14--21
28	57600 / V32 / LAPM/ V.42bis / 14400	Same	39	18--29

At 28 dB, the connection is lost after 17 seconds. This shows the incompatibility between different chipsets. The Signal level and Quality represents the characteristics of the channel between the two modems measured by the Starcomm modem's chipset.

Test # 4:

Machine 1: Starcomm 14.4 modem
Machine 2: Zoom Dual Mode (56 k)

Chipset on Machine # 1 was Rockwell 93
Chipset on Machine # 2 was Lucent

Teltone Parameters: Impedance = 900Ω, Loop Current = 35mA

Attn (dB)	M/C # 1	M/C # 2	Signal Level	Signal Quality
4	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32/LAPM/V42bis/14400	17	6--8
14	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32/LAPM/V42bis/14400	27	6--9
24	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32/LAPM/V42bis/14400	36	10--14
26	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32/LAPM/V42bis/14400	38	14--19
28	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32/LAPM/V42bis/14400	38	14--19
29	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32/LAPM/V42bis/14400	42	18--26
30	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32/LAPM/V42bis/14400	42	19-29

Note: The connection at 29 dB was dropped after 1 minute and 14 seconds where as the last connection only lasted 44 seconds.

Test # 5:

Machine 1: Starcomm 14.4 modem
Machine 2: Best Data (56 k)

Chipset on Machine # 1 was Rockwell 93
Chipset on Machine # 2 was Conexant (Rockwell)

Teltone Parameters: Impedance = 900Ω, Loop Current = 35mA

Attn (dB)	M/C # 1	M/C # 2	Signal Level	Signal Quality
4	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32b/LAPM/V42bis/14400	15	4--7
14	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32b/LAPM/V42bis/14400	24	4--7
24	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32b/LAPM/V42bis/14400	35	10--13
26	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32b/LAPM/V42bis/14400	36	12--17
28	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32b/LAPM/V42bis/14400	38	16--20
30	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32b/LAPM/V42bis/14400	39	21--29
32	57600 / V32 / LAPM/ V.42bis / 14400	115200/V.32b/LAPM/V42bis/14400	39	21--29
34	57600/V32/LAPM/V.42bis/**12000**	115200/V.32b/LAPM/V42bis/**12000**	41	15--21
36	No Connection			

Note: This definitely shows that two modems with the same chipset may communicate somewhat better than two modems with different chipset, however this was not observed in all cases.

Test # 6:

Machine 1: US Robotics 56 k
Machine 2: Best Data (56 k)

Chipset on Machine # 1 was US Robotics
Chipset on Machine # 2 was Conexant (Rockwell)

Teltone Parameters: Impedance = 900Ω, Loop Current = 35mA

Attn (dB)	M/C # 1	M/C # 2	Signal Level	Signal Quality
4	33600/ARQ/V34/LAPM/V.42bis	33600/V34/LAPM/V.42bis	16	18--20
14	33600/ARQ/V34/LAPM/V.42bis	33600/V34/LAPM/V.42bis	27	21--29
16	33600/ARQ/V34/LAPM/V.42bis	33600/V34/LAPM/V.42bis	28	28--36
18	31200/ARQ/V34/LAPM/V.42bis	33600/V34/LAPM/V.42bis	31	24--31
20	28800/ARQ/V34/LAPM/V.42bis	28800/V34/LAPM/V.42bis	33	22-30
24	24000/ARQ/V34/LAPM/V.42bis	24000/V34/LAPM/V.42bis	37	21--27
26	21600/ARQ/V34/LAPM/V.42bis	21600/V34/LAPM/V.42bis	39	33--41
28	21600/ARQ/V34/LAPM/V.42bis	21600/V34/LAPM/V.42bis	40	29--36
30	19200/ARQ/V34/LAPM/V.42bis	19200/V34/LAPM/V.42bis	43	28--35
32	DOES NOT CONNECT			

Test # 7:

Machine 1: US Robotics 56 k
Machine 2: Best Data (56 k)

Chipset on Machine # 1 was US Robotics
Chipset on Machine # 2 was Conexant (Rockwell)

Teltone Parameters: Impedance = 900Ω, Loop Current = 35mA

Attn (dB)	M/C # 1	M/C # 2	Noise Level
4	33600/ARQ/V34/LAPM/V.42bis	33600/V34/LAPM/V.42bis	17
14	31200/ARQ/V34/LAPM/V.42bis	31200/V34/LAPM/V.42bis	37
18	28800/ARQ/V34/LAPM/V.42bis	28800/V34/LAPM/V.42bis	58
22	26400/ARQ/V34/LAPM/V.42bis	26400/V34/LAPM/V.42bis	61
24	24000/ARQ/V34/LAPM/V.42bis	24000/V34/LAPM/V.42bis	118
25	24000/ARQ/V34/LAPM/V.42bis	24000/V34/LAPM/V.42bis	153
26	21600/ARQ/V34/LAPM/V.42bis	21600/V34/LAPM/V.42bis	195
28	19200/ARQ/V34/LAPM/V.42bis	19200/V34/LAPM/V.42bis	309
30	DOES NOT CONNECT		

Note: Here the noise level readings were given by the lucent chipset by the use of the command 'ATI11'

Test # 8:

Machine 1: Zoom Dual mode 56 k
Machine 2: Best Data (56 k)

Chipset on Machine # 1 was Lucent
Chipset on Machine # 2 was Conexant (Rockwell)

Teltone Parameters: Impedance = 900Ω, Loop Current = 35mA

Attn (dB)	M/C # 1	M/C # 2	Noise Level
4	33600/V34/LAPM/V.42bis	33600/V34/LAPM/V.42bis	17
14	31200/V34/LAPM/V.42bis	31200/V34/LAPM/V.42bis	29
18	31200/V34/LAPM/V.42bis	31200/V34/LAPM/V.42bis	46
20	28800/V34/LAPM/V.42bis	28800/V34/LAPM/V.42bis	76
22	26400/V34/LAPM/V.42bis	26400/V34/LAPM/V.42bis	105
24	24000/ARQ/V34/LAPM/V.42bis	24000/V34/LAPM/V.42bis	140
27	21600/ARQ/V34/LAPM/V.42bis	21600/V34/LAPM/V.42bis	254
29	19200/ARQ/V34/LAPM/V.42bis	19200/V34/LAPM/V.42bis	401
30	No Carrier		

C.4. Phase IV Tests

In this phase three different types of tests were performed:

1. Combination of noise and attenuation on modem performance,
2. Modem connection from various actual telephone lines, and
3. Modem line quality tests on multiple FDOT modem lines.

The combination tests were conducted to further investigate the problem of 56K modems calling to lower speed modems. In these tests, the line attenuation (both directions) was fixed at 24 dB and the noise level was varied to determine the maximum noise where reliable connections could be established. The results of these tests are summarized in Table 6 of Section 3.3.

Modem connection speeds were checked when dialing from various locations in the next set of tests. Four 56K modems were each used to connect to three different dial-up lines (Internet access points). This was repeated at two different residential sites (Test Sites #1 & 2), a lab located in room A322 at the FAMU-FSU College of Engineering, and from the FDOT facility at Springhill Road. At each test site each modem was used to call three different Internet access lines: two lines at the FAMU-FSU College of Engineering (350-9609 and 350-9707) and one at the FSU main campus (644-2700). The connection speed was recorded for each connection. The results of the tests are listed in the tables below.

Test Site #1: Home		
Connection site: 350-9609		
Modem used	Connect speed (Procomm)	Dial-up networking
Lucent Winmodem	28800/V42bis	28800
Best Data	28800V34/LAPM/V42BIS	28800
US Robotics	28800/ARQ/V34/LAPM/V42B	28800
Zoom	28800/V42bis	28800
Connection site: 350-9707		
Modem used	Connect speed (Procomm)	Dial-up networking
Lucent Winmodem	28800/V42bis	28800
Best Data	28800V34/LAPM/V42BIS	28800
US Robotics	28800/ARQ/V34/LAPM/V42B	28800
Zoom	28800/V42bis	28800
Connection site: 644-2700		
Modem used	Connect speed (Procomm)	Dial-up networking
Lucent Winmodem	26400/V42bis	26400
Best Data	28800V34/LAPM/V42BIS	26400
US Robotics	28800/ARQ/V34/LAPM/V42B	28800
Zoom	28800/V42bis	28800

Site # 2: Friend's place		
Connection site: 350-9609		
Modem used	Connect speed (Procomm)	Dial-up networking
Lucent Winmodem	44000/V42bis	44000
Best Data	46667/V34/LAPM/V42BIS	45333
US Robotics	44000/ARQ/V90/LAPM/V42B	44000
Zoom	42666/V42bis	42666
Connection site: 350-9707		
Modem used	Connect speed (Procomm)	Dial-up networking
Lucent Winmodem	44000/V42bis	44000
Best Data	45333/V34/LAPM/V42BIS	45333
US Robotics	44000/ARQ/V90/LAPM/V42B	44000
Zoom	42666/V42bis	42666
Connection site: 644-2700		
Modem used	Connect speed (Procomm)	Dial-up networking
Lucent Winmodem	37333/V42bis	37333
Best Data	45333/V34/LAPM/V42BIS	45333
US Robotics	42666/ARQ/V90/LAPM/V42B	42666
Zoom	42666/V42bis	42666

Test Site # 3: COE Lab		
Connection site: 350-9609		
Modem used	Connect speed (Procomm)	Dial-up networking
Lucent Winmodem	49333/V42bis	49333
Best Data	48000/V34/LAPM/V42BIS	48000
US Robotics	49333/ARQ/V90/LAPM/V42B	49333
Zoom	48000/V42bis	48000
Connection site: 350-9707		
Modem used	Connect speed (Procomm)	Dial-up networking
Lucent Winmodem	49333/V42bis	46666
Best Data	46667/V34/LAPM/V42BIS	49333
US Robotics	49333/ARQ/V90/LAPM/V42B	49333
Zoom	48000/V42bis	50666
Connection site: 644-2700		
Modem used	Connect speed (Procomm)	Dial-up networking
Lucent Winmodem	49333/V42bis	50666
Best Data	48000/V34/LAPM/V42BIS	48000
US Robotics	50666/ARQ/V90/LAPM/V42B	49333
Zoom	48000/V42bis	48000

Test Site # 4: FDOT Lab		
Connection site: 350-9609		
Modem used	Connect speed (Procomm)	Dial-up networking
Lucent Winmodem	28800/V42bis	28800
Best Data	31200/V34/LAPM/V42BIS	31200
US Robotics	33333/ARQ/V90/LAPM/V42B	31200
Zoom	28000/V42bis	31200
Connection site: 350-9707		
Modem used	Connect speed (Procomm)	Dial-up networking
Lucent Winmodem	28800/V42bis	28800
Best Data	31200/V34/LAPM/V42BIS	31200
US Robotics	36000/ARQ/V90/LAPM/V42B	34666
Zoom	31200/V42bis	31200
Connection site: 644-2700		
Modem used	Connect speed (Procomm)	Dial-up networking
Lucent Winmodem	26400/V42bis	26400
Best Data	31200/V34/LAPM/V42BIS	31200
US Robotics	36000/ARQ/V90/LAPM/V42B	36000
Zoom	29333/V42bis	29333

Also, a pair of modem line quality testers was used to measure the quality of several modem lines at the FDOT Springhill Road facility, and all the data collection lines in the Burns building. The results of these tests are summarized in Table 7 of Section 3.3.

APPENDIX D – MODEM TEST SETUP AND PROCEDURES

D.1. Hardware Setup for the Teltone TLE-A-01

The Teltone TLE-A-01 was used to perform the attenuation and noise tests on each combination of modems. The following contains a description of the hardware configuration for the tests and a brief description of the software setup for controlling the Teltone TLE.

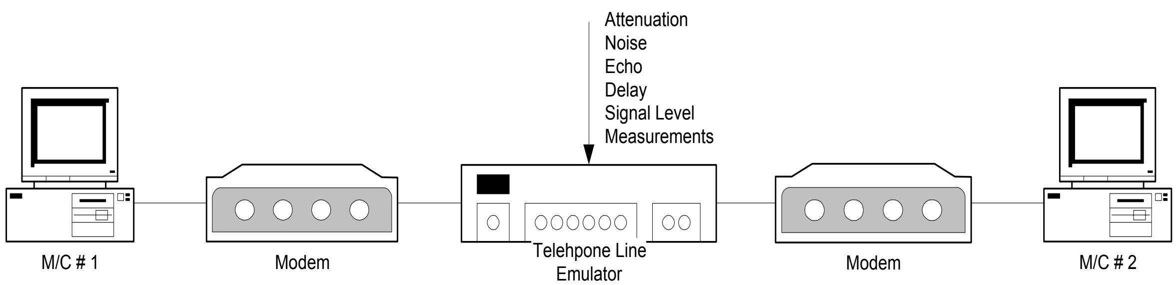


Figure D1. Test Set-Up for Noise and Attenuation Tests with Teltone TLE

Figure D1 shows two personal computers, two modems and a telephone line emulator. The function of the telephone line emulator (TLE) is to simulate the function of the telephone office. The TLE is a hardware device accompanied by software to add additional features for simulating conditions observed on a regular telephone line. It has four ports i.e. it can dial from one port to the other three ports.

Note: In the experiments conducted, the leftmost PC is referred as Machine # 1(M/C # 1) and the rightmost PC is referred as M/C # 2

Equipment Connection Requirements:

In the experiments conducted, M/C # 1 requires two serial ports, whereas M/C # 2 requires one serial port. The first step is to connect the TLE to serial port 1 on M/C # 1. Then connect the modem to serial port 2, also M/C # 1. Finally, connect the other modem to the serial port 1 of M/C # 2.

Settings for M/C # 1:

Serial Port 1 (Comm 1): Teltone TLE-A01 unit
Serial Port 2 (Comm 2): External Modem

Settings for M/C # 2:

Serial Port 1: External Modem

Then connect the TLE to the two modems using telephone cables. For example, connect modem on the left to port 1 on TLE and connect the other modem to port 3. Once everything is connected, power-up the modems and the TLE with there respective power supplies.

D.2. Software Set-up: ProComm and the TLE_PC Software

The next step is to install the software required for carrying out the experiments.

Communications Software:

Since the PCs should recognize the modems attached, the first step is to install the modem drivers. Follow the modem manual for this step.

Then install the ProComm plus software on both the PCs. This software has variety of functions in it including the BBS (Bulletin Board Software) feature. A CD comes with the software and can be easily installed. Incase of difficulties, refer to the ProComm plus manual.

Finally, install the TLE software. The TLE-A01 (Teltone) unit has to be connected to com-port 1 on machine 1. If connected to com-port 2 it would not be identified as connected and therefore the settings for local loop parameters, signal measurements, etc would be default and cannot be changed.

The software is installed from CD and an updated version can be obtained from the website http://www.teltone.com. After installing TLE, on serial port 1, and the software, the experimental setup is completed. To change settings of the parameters, go to start (from desktop), then to Programs and then to TLE PC to get the current settings.

There are a variety of features that can be used on the Teltone unit. Some of the most prominent ones are: Attenuation (Local loop parameters), Impairments (echo and white Noise), Signal level measurements, etc

Checking Teltone Installation:

After installing the Teltone software on M/C #1, left click ***Start*** button at the bottom of the screen. Then go to ***Programs***, select ***TLE*** and then ***TLE PC*** as shown in Figure 2. This should open the TLE software as shown in Figure D3. The program first checks if the hardware unit is connected. To manually check, click ***Comm,*** and select ***check com1.*** This should verify the connection of the hardware by stating ***TLE DETECTED.*** This is demonstrated in Figures D4 and D5, respectively.

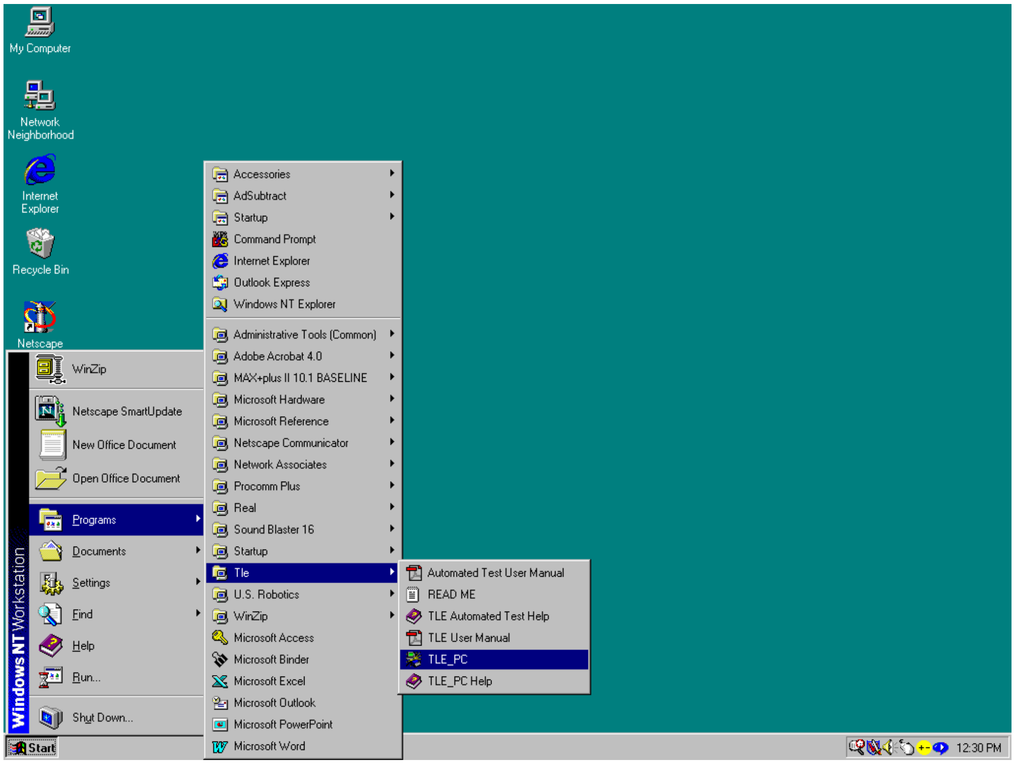


Figure D2 – Opening TLE Software

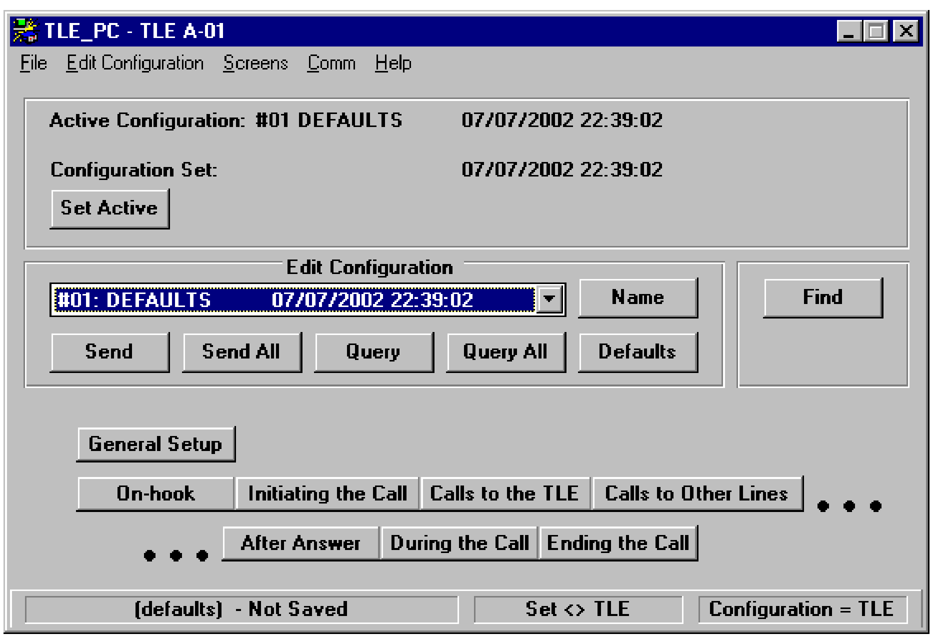


Figure D3 – TLE main screen

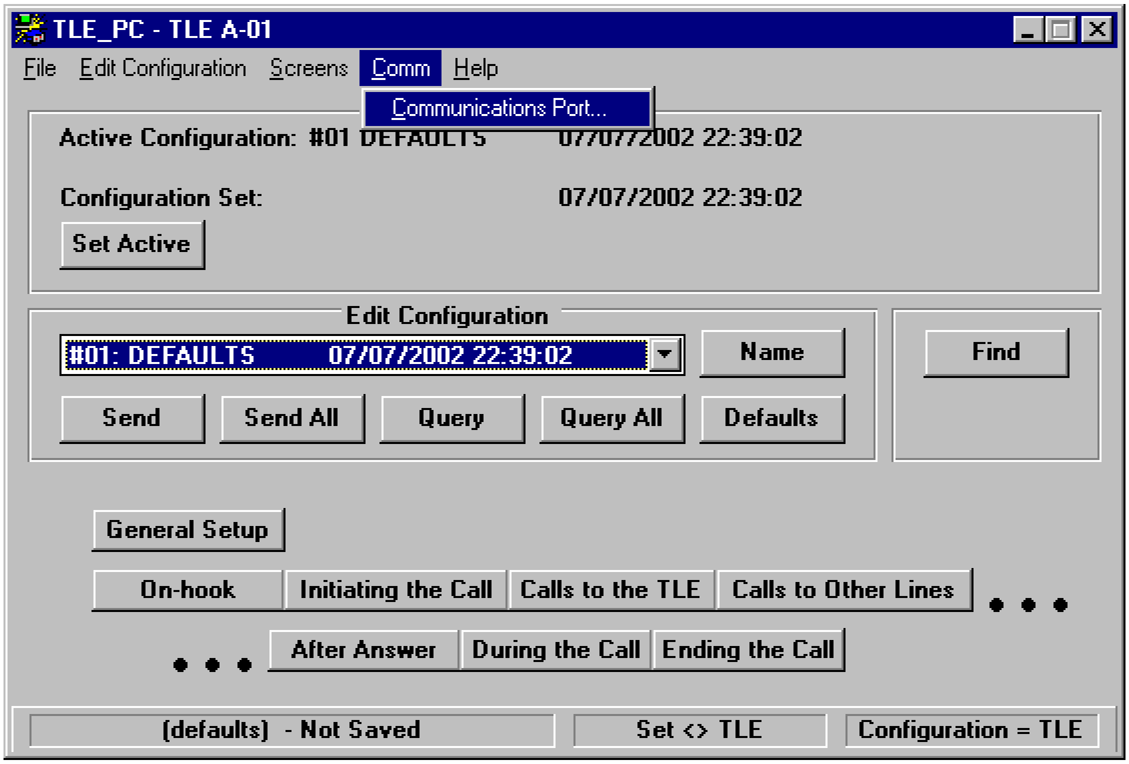


Figure D4 – Manually Checking Connection of TLE Hardware

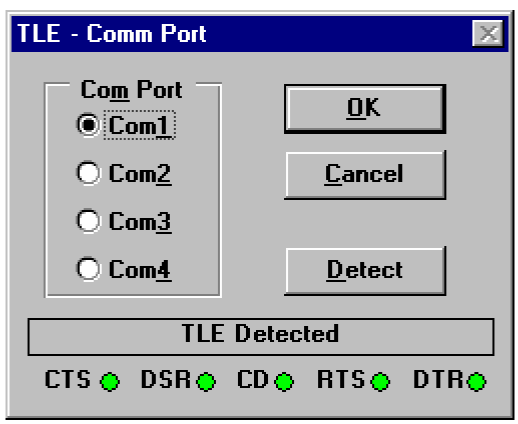


Figure D5 – Verification of TLE Hardware Connected to PC

D.3. Setting Parameters on TLE: White Noise and Attenuation

The Teltone TLE has the capability to adjust many parameters associated with a telephone line including ring frequency, echo, attenuation, white noise, impedance and sidetones. The two parameters used in these tests to evaluate the performance of the modems were *attenuation* and *white noise*.

Setting attenuation:

There are four ports (telephone line connections) in the TLE. The attenuation is set on any port (line) by opening the ***Screens*** menu and selecting ***Loop Parameters***. Figure D6 demonstrates this step graphically.

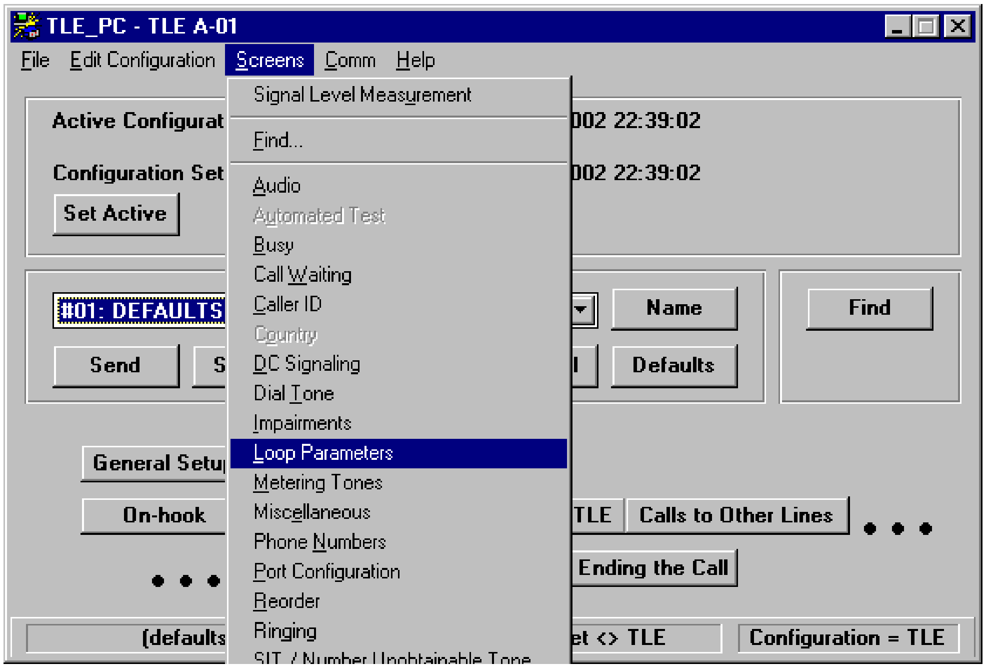


Figure D6 – Step to Set Attenuation on TLE Ports

The default levels are already set into the system through installation. At these levels, the communication channels are assumed to behave ideally. Figure D7 illustrates the default screen for attenuation settings. To change the attenuation on any of the four ports (lines), just change the *Line Receive Attenuation* parameter. Figure D8 shows how the screen would look after setting 30dB on *Line 1* and *Line 3* on the TLE.

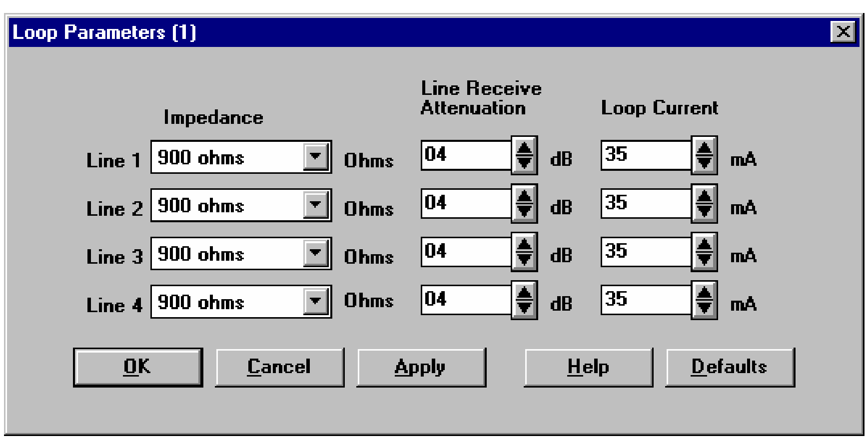


Figure D7 – Default screen for setting Attenuation on the any or all lines of TLE

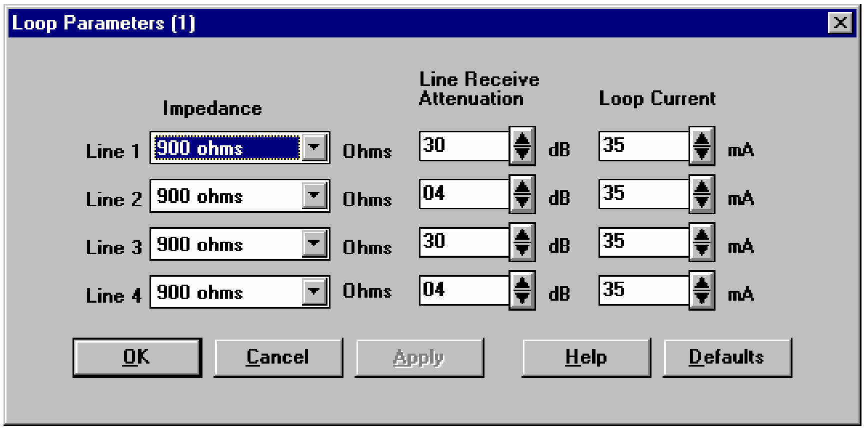


Figure D8 – Setting attenuation of 30dB on Line 1 and Line3

Setting white noise:

To set the white noise parameters, click the ***screens*** menu and select ***Impairment***, as demonstrated in Figure D9.

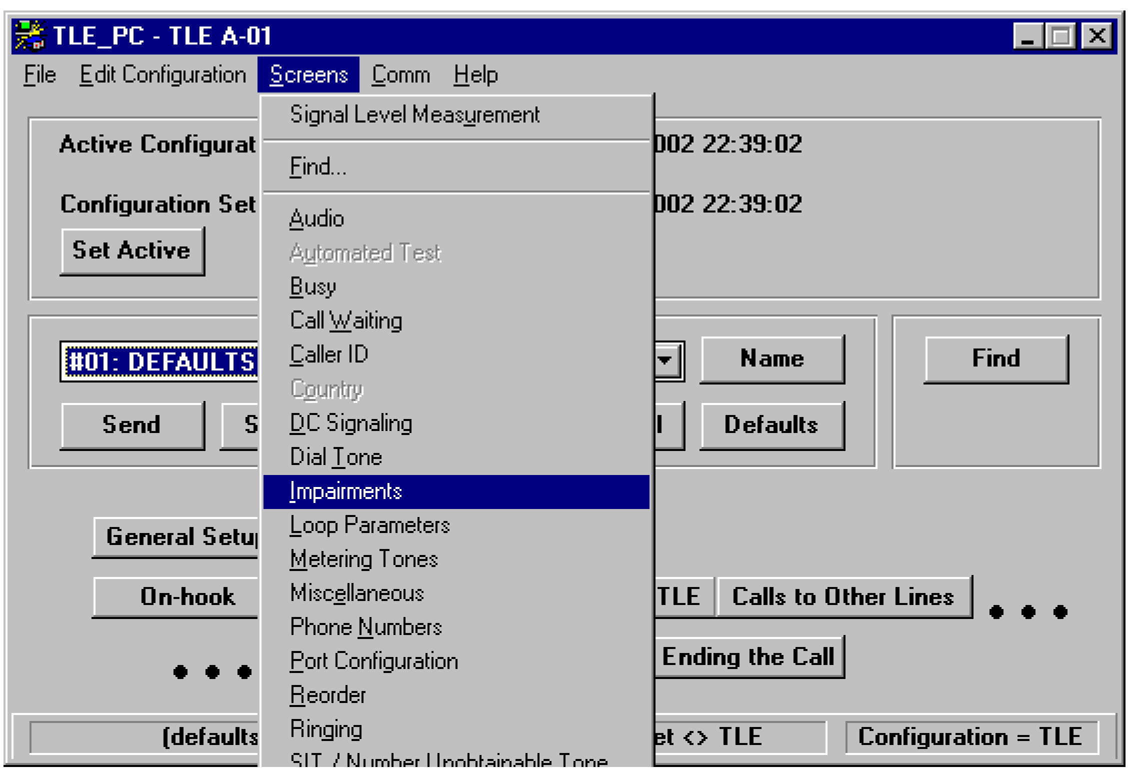


Figure D9 – Setting White Noise using TLE

By following the previous step, illustrated in Figure D9, a box pops up that allows the user to set up white noise levels on the TLE lines. This pop-box is illustrated in Figure D10.

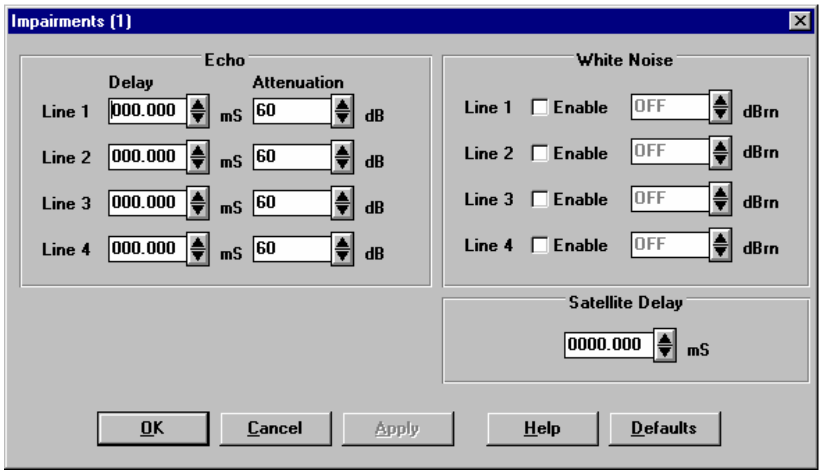


Figure D10 – Graphical User Interface for setting white noise

To set the white noise levels on any of the line, check the box using the mouse. For example, Figure D11 demonstrates how the graphical user interface would look like after the user sets the white noise at 40 dBrn on *Line 1* and *Line 3*.

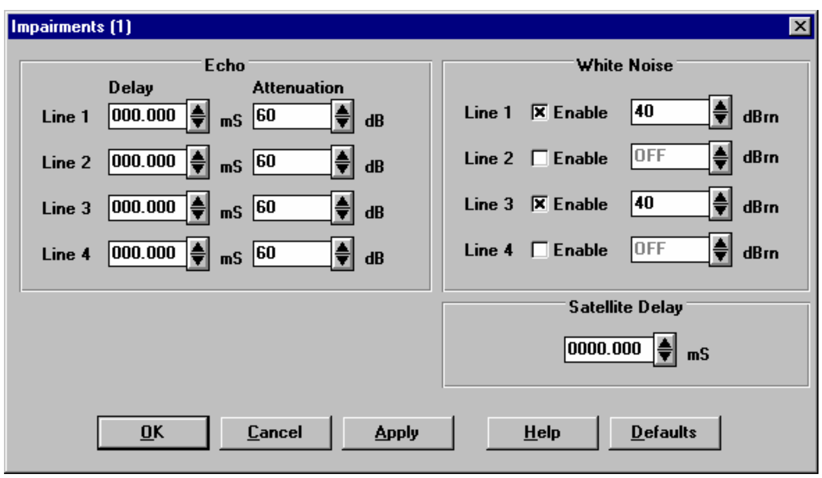


Figure D11 – Demonstration of setting white noise on Line 1 and Line 3

D.4. Using ProComm Plus

The following instructions need to be carried out on both the PCs. The first step is to start the ProComm plus software. After installation the ProComm Software could either be accessed from the desktop or through the *Start* menu as indicated in Figure D12.

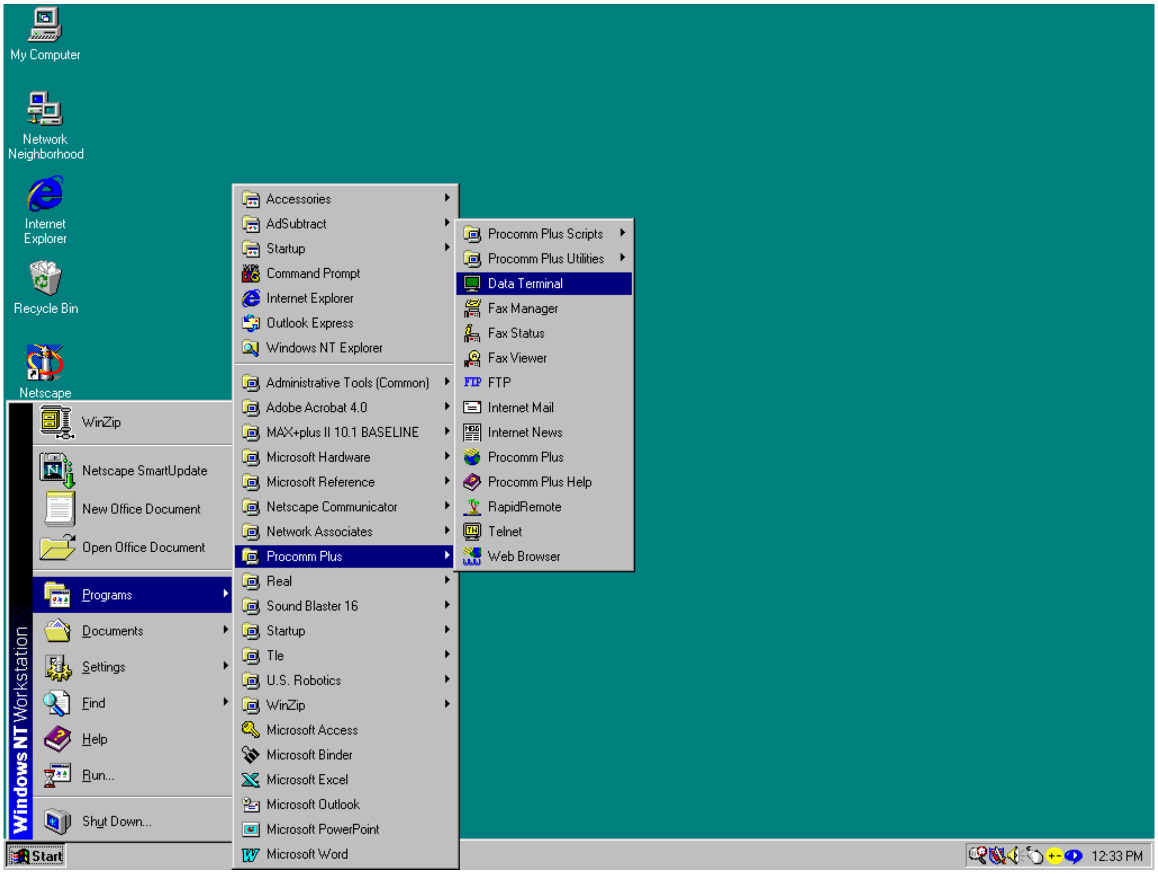


Figure D12 – Starting ProComm Plus Software

After the ProComm plus software is running, the first step is to check if the modem you installed is the active modem ProComm would use to initiate the calls. The way to check the current active modem is easy; the active modem is shown at the bottom of the screen. But if the modem needs to be changed, just go to the *Options* menu, select *Systems Options* and then select *Modem Connection*. Figure D13 demonstrates both the above-mentioned features: checking for current modem at the bottom of the screen and also changing the current modem.

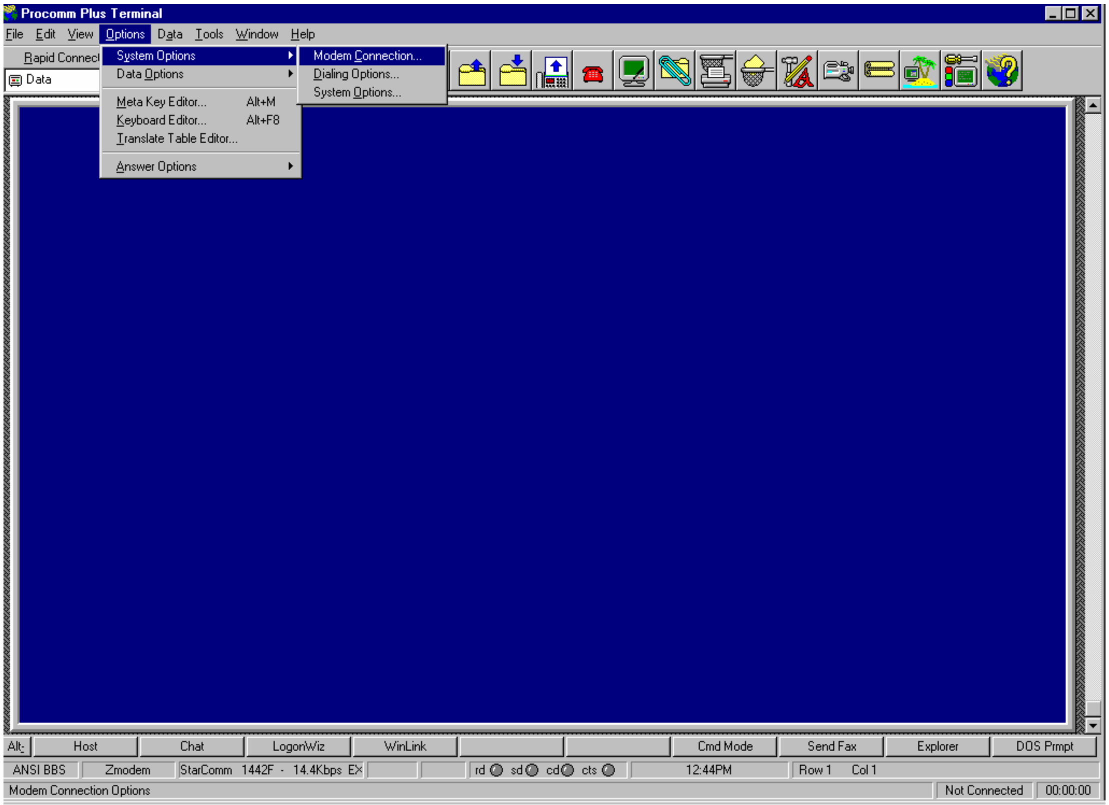


Figure D13 – Viewing current modem & Changing current modem

Following the steps in Figure D13, a setup dialog box pops up. This Setup box can be used to see the current modem and can also be used to change the modem. Figure D14 illustrates the Setup box.

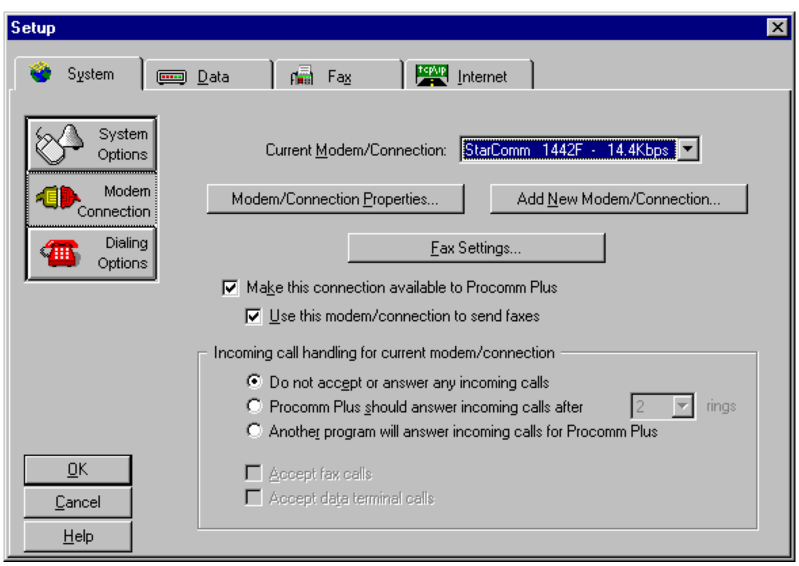


Figure D14 – Setup Box

Figure D15 shows a list of modems that can be selected as the current modem. All these modems were first installed as per the instructions in their manuals and automatically added to the ProComm list.

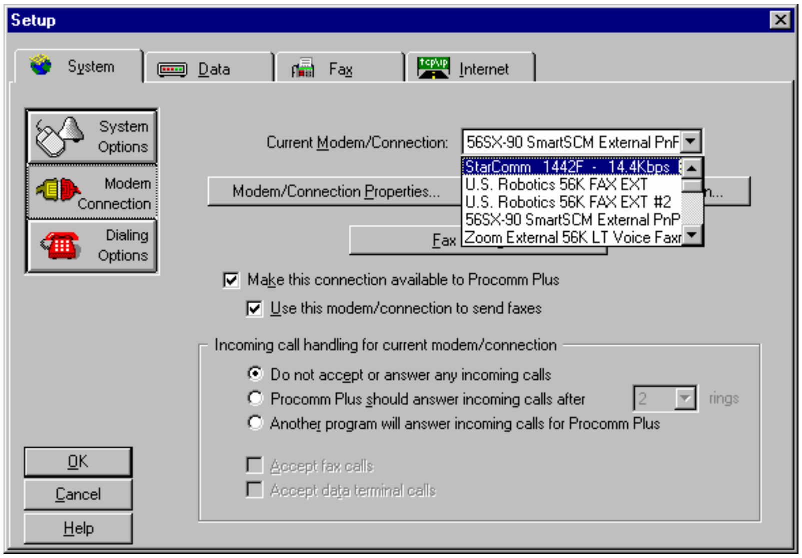


Figure D15 – Selecting Current Modem

Once the modem selection process is finished, the next step is to get the modem in to the command mode so that the process of dialing the connection can take place. To get the modem into the command mode, just go to the main window of ProComm Plus and select *Data*, and then *Modem command Mode*.

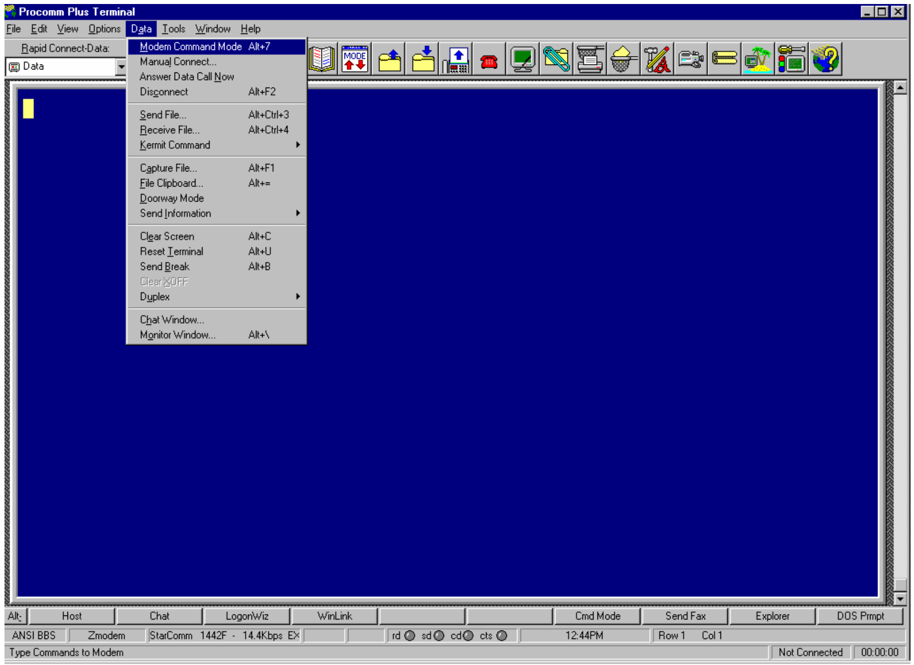


Figure D16 – Setting modem in command mode

Once the mode is set in command mode, the modem should respond with *ok*, to demonstrate it is ready to accept commands. After all the hardware and software are setup properly, the task to conduct the experiments follows.

Common Modem AT Commands used for conducting experiments:

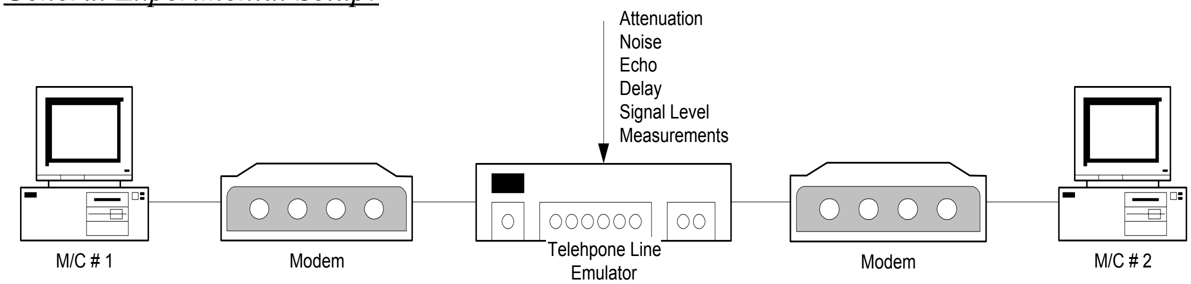
A few basic modem commands are used almost every time and are therefore mentioned in this section. For more commands, refer to the modem manual.

The first command is *ATDTxxx*. The command stands for Attention, Dial Tone and “xxx” represents the number that is to be dialed. The modem that needs to answer the incoming call uses the command *ATA*, which stands for Attention, Auto Answer.

Once the connection is established, ProComm Plus displays the protocols used to establish the connection at the speed of the connection. To get further details from the modem, specific commands in the modem’s manual are used. A list of common AT commands and definitions is given in Appendix E for reference. Refer to the documentation for the particular modem to verify the AT commands specific to that modem.

D.5. Test Procedures

General Experimental Setup:



Required Hardware Equipments

a) M/C # 1 with 2 serial port connections
b) 2 modems (for example: Two Starcomm Modems)
c) Telephone Line Emulator (TLE) unit
d) M/C # 2 with 1 serial port
e) Three serial port (RS-232) cables + two telephone line cables + power supplies of each equipment present in the experimental setup

Software Requirements

a) M/C # 1 requires installation of TLE software, the Procomm software, and the modem drivers of the modem tested. (Appendix D.2)
b) M/C # 2 requires the installation of the Procomm Software and the modem drivers of the modem installed with this PC.

Figures of the experimental setup:

(Front view)

To further explain the figure illustrated above, the TLE unit (black box in between two modems) is connected to serial port 1 of the desktop computer (M/C # 1), and the modem (close to the M/C # 1) is connected to serial port 2. The telephone line connection is made between the modems and the TLE unit as observed from the figure. The Laptop is only connected to the modem (not to the TLE unit, as illustrated in the figure below), which in turn is connected to the TLE unit through the telephone line cable.

(Back-view of experimental setup)

After the experimental setup is completed and the software installed (as mentioned in appendix D.2.) the actual tests can be conducted.

D.5.1 Modem Compatibility Test Procedure (Phase I):

i) Make sure all the hardware connections are configured as illustrated in the above figures. Note that there are four ports on the TLE. Connect port 1 to the modem attached to computer #1 (M/C#1) and connect port 3 to the modem attached to computer #2 (M/C#2).

ii) Make sure all required software is installed properly on each PC as mentioned in Appendix D.2. Also follow the verification process mentioned to ensure proper installation of TLE software.

iii) Verify that the TLE impedance is 900 Ω (default) and the loop current is 35 mA (default). This process is mentioned in APPENDIX D.3 and needs only to be carried out on M/C#1.

iv) Use the TLE software on M/C#1 to set the white noise and attenuation levels to a minimum. The minimum level for attenuation is 4 dB. The white noise is switched off. Refer to Appendix D.3 to see the steps for setting the white noise and the attenuation levels.

v) Open the Procomm Plus Software (on both M/C#1 and M/C#2) and set the active modem in Procomm to the modem attached (under test) (as illustrated in Appendix D.4).

vi) After the Procomm Plus software is in command mode on both the computers (appendix D. 4), type "*ATDT103*" from M/C#1. This command instructs the Procomm software to dial from port 1 to port 3 of the TLE. The Procomm Plus software on M/C#2 indicates "ring" command, which implies that it is receiving a call that needs to be answered. Therefore, type "ATA" on M/C#2. This command instructs the modem on M/C#2 to answer the call initiated by M/C#1. Once ENTER is pressed, the two computers are connected through the modems and TLE unit, and the Procomm Plus software indicates the speed at which the connection was made and the protocols used.

vii) Now to transfer a file see *Figure D16 – setting modem in command mode*, and observe the *Send File* option. Click on it and select a file to send and note the time it takes to transfer the file (seconds) and the file size (Bytes). To calculate throughput, multiple the file size (in bytes) by 8 and divide by the time required to transfer the file.

viii) The protocols indicated in step 6 determine the performance of the two modems under ideal conditions. The numbers in step 7 are used to estimate the time it would need to send a file at that particular connection (if achieved in the field).

D.5.2 White Noise Test Procedure (Phase II)

i) Make sure all the hardware connections are configured as illustrated in the above figures. Note that there are four ports on the TLE. Connect port 1 to the modem attached to computer #1 (M/C#1) and connect port 3 to the modem attached to computer #2 (M/C#2).

ii) Make sure all required software is installed properly on each PC as mentioned in Appendix D.2. Also follow the verification process mentioned to ensure proper installation of TLE software.

iii) Verify that the TLE impedance is 900 Ω (default) and the loop current is 35 mA (default). This process is mentioned in APPENDIX D.3 and needs only to be carried out on M/C#1.

iv) Use the TLE software on M/C#1 to set the attenuation to the minimum value of 4dB on lines 1 and 3 of the TLE. Refer to Appendix D.3 to see the steps for setting the attenuation.

v) Open the Procomm plus software on both M/C#1 and M/C#2, and set the active modem in Procomm to the modem attached (under test) (as illustrated in Appendix D.4).

vi) Use the TLE software on M/C#1 to set the white noise to the desired level (e.g. the specified level) on lines 1 and 3 of the TLE. Refer to Appendix D.3 to see the steps for setting the white noise level.

vii) Set the Procomm Plus software into the command mode on both the computers (Appendix D. 4) and type "*ATDT103*" from the M/C#1. This command instructs the Procomm software to dial from port 1 to port 3 of the TLE. The Procomm Plus software on M/C#2 indicates "ring" command, which implies that it is receiving a call that needs to be answered. Therefore, type "ATA" on M/C#2. This command instructs the modem on M/C#2 to answer the call initiated by M/C#1. Once ENTER is pressed, the two computers are connected through the modems and TLE unit, and the Procomm Plus software indicates the speed at which the connection was made and the protocols used.

viii) Wait for two minutes to see if the connection remains valid or observe if it gets disconnected. A file may be transmitted as was done step (vii) of the compatibility test, if desired.

ix) If modems remains connected the modems pass the test.

x) If the modems disconnect or the file will not transfer, then the modem fails the test. Steps (vi) to (viii) can be repeated at lower noise levels to determine the maximum white noise tolerated by the modems.

D.5.3 Attenuation Test Procedure (Phase III)

xi) Make sure all the hardware connections are configured as illustrated in the above figures. Note that there are four ports on the TLE. Connect port 1 to the modem attached to computer #1 (M/C#1) and connect port 3 to the modem attached to computer #2 (M/C#2).

xii) Make sure all required software is installed properly on each PC as mentioned in Appendix D.2. Also follow the verification process mentioned to ensure proper installation of TLE software.

xiii) Verify that the TLE impedance is 900 Ω (default) and the loop current is 35 mA (default). This process is mentioned in APPENDIX D.3 and needs only to be carried out on M/C#1.

xiv) Use the TLE software on M/C#1 to turn off the white noise on lines 1 and 3 of the TLE. Refer to Appendix D.3 to see the steps for setting the white noise level.

xv) Open the Procomm plus software on both M/C#1 and M/C#2, and set the active modem in Procomm to the modem attached (under test) (as illustrated in Appendix D.4).

xvi) Use the TLE software on M/C#1 to set the attenuation to the desired level (e.g. the specified level) on lines 1 and 3 of the TLE. Refer to Appendix D.3 to see the steps for setting the attenuation level.

xvii) Set the Procomm Plus software into the command mode on both the computers (Appendix D. 4) and type "*ATDT103*" from the M/C#1. This command instructs the Procomm software to dial from port 1 to port 3 of the TLE. The Procomm Plus software on M/C#2 indicates "ring" command, which implies that it is receiving a call that needs to be answered. Therefore, type "ATA" on M/C#2. This command instructs the modem on M/C#2 to answer the call initiated by M/C#1. Once ENTER is pressed, the two computers are connected through the modems and TLE unit, and the Procomm Plus software indicates the speed at which the connection was made and the protocols used.

xviii) Wait for two minutes to see if the connection remains valid or observe if it gets disconnected. A file may be transmitted as was done in step (vii) of the compatibility test, if desired.

xix) If modems remains connected the modems pass the test.

xx) If the modems disconnect or the file will not transfer, then the modem fails the test. Steps (vi) to (viii) can be repeated at lower attenuation levels to determine the maximum white noise tolerated by the modems.

APPENDIX E - COMMON AT MODEM COMMANDS

A	Answer incoming call
A/	Repeat last command. (Don't preface with AT. Enter usually aborts.)
D	Dial the following number and then handshake in originate mode.
	Dial Modifiers (These are common but most modems will have more.)
P	Pulse dial
T	Touch Tone dial
W	Wait for second dial tone
,	Pause for time specified in register S8 (usually 2 seconds)
;	Remain in command mode after dialing
!	Flash switch-hook (Hang up for a half second as in transfering a call)
E	Will not echo commands to the computer (also E0)
E1	Will echo commands to the computer (so one can see what one types)
H	On Hook (hang up, also **H0**)
H1	Off Hook (phone picked up)
I	Inquiry, Information, or Interrogation
	(This command is very model specific. I0 usually returns a number or code, while higher numbers often provide much more useful information.)
L	Speaker Loudness (**L0** off or low volume) -\
L1	Low volume } Modems with volume control
L2	Medium volume (usual default) } knobs will not have these.
L3	Loud or high volume -/
M	Speaker off (**M0**) (**M3** is also common, but different on many brands)
M1	Speaker on until remote carrier detected (until the other modem is heard)
M2	Speaker is always on (data sounds are heard after CONNECT)
O	Return Online (**O0** see also **X1** as dial tone detection may be active)
O1	Return Online after an equalizer retrain sequence
Q	Quiet mode **Q0** displays result codes, user sees command responses (e.g. OK)
Q1	Quiet mode, result codes are suppressed, user does not see responses
Sn?	Query the contents of S-register n
Sn=r	Store the value r in S-register n
V	non-Verbal (Numeric result codes **V0**)
V1	Verbal english result codes (*e.g.* CONNECT, BUSY, NO CARRIER etc.)
X	Hayes Smartmodem 300 compatible result codes (**X0**) (Many have more than 4)
X1	Usually adds connection speed to basic result codes (*e.g.* CONNECT 1200)
X2	Usually adds dial tone detection (preventing blind dial and sometimes **ATO**)
X3	Usually adds busy signal detection
X4	Usually adds both busy signal and dial tone detection
Z	Reset modem to stored configuration (Z0, Z1 etc. for multiple profiles)
	(Same as &F (factory default) on modems with out NVRAM (non volatile memory)
&C0	Carrier detect (CD) signal always on
&C1	Carrier detect indicates remote carrier (usual prefered default)

&D0 Data Terminal Ready (DTR) signal ignored (**See your manual** on this one!)
&D1 If DTR goes from On to Off the modem goes into command mode (**some** modems)
&D2 Some modems hang upon DTR On to Off transition. (usual prefered default)
&F Factory defaults (Most modems have several defaults **&F1**, **&F2**, etc.)
&P (**&P0**) U.S./Canada pulse dialing 39% make/ 61% break ratio
&P1 U.K./Hong Kong pulse dialing 33% make/ 67% break ratio
&T Model specific self tests on some modems
&V View active (and often stored) configuration profile settings (or **ATI4**)
&W Store profile in NVRAM (&W0, &W1 etc. for multiple profiles)
Some settings cannot be stored. These often don't show on **&V** or **ATI4**
&Zn=x Store number x in location n for AT DS on some modems

S-registers

Register	**Range**	**Default**	**Function**
S0	0-255 rings	1-2	Answer on ring number <u>Don't answer if 0</u>
S1	0-255 rings	0	If S0>0 this register counts incoming rings
S2	0-127 ASCII	43 +	Escape to command mode character S2>127 no ESC
S3	0-127 ASCII	13	CR Carriage return character
S4	0-127 ASCII	10	LF Line feed character
S5	0-32,127 ASCII	8	BS Backspace character
S6	2-255 seconds	2	Dial tone wait time (blind dialing, see **X**n)
S7	1-255 seconds	30-60	Wait time for remote carrier
S8	0-255 seconds	2	Comma pause time used in dialing
S9	1-255 1/10 sec.	6	Carrier detect time required for recognition
S10	1-255 1/10 sec.	7-14	Time between loss of carrier and hang up
S11	50-255 msec.	70-95	Duration and spacing of tones when tone dialing
S12	0-255 1/50 sec.	50	Guard time for pause around +++ command sequence

Many modems have dozens, even hundreds, of S registers, but only the first dozen or so are fairly standard. They are changed with a command like ATSn=N, and examined with ATSn? (*e.g.* **AT S10=7 S1?** would tell the modem not to hang up for seven seconds should it not hear the answering modem, and return the number of times the phone last rang.)

Appendix C
Telephone Line Surge Protection Task Report

This appendix includes the report detailing the efforts on the telephone line surge suppressors.

Technical Report

Telemetered Traffic Monitoring Site (TTMS) Telephone Line Surge Protection

PROJECT:
Improving Operation of FDOT Telemetered Traffic Monitoring Sites
(FDOT Contract No. BC-596, FSU Project No. 613054139)

Submitted by:

FAMU-FSU College of Engineering
2525 Pottsdamer Street
Tallahassee, FL 32310-6046

Principal Investigator:

Bruce A. Harvey, Ph. D., Assistant Professor
Department of Electrical and Computer Engineering
Phone: (850) 410-6451
Fax: (850) 410-6479
Email: bharvey@eng.fsu.edu

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EXECUTIVE SUMMARY

Lightning is a significant problem for the over 300 Telemetered Traffic Monitoring Sites (TTMSs) currently in use by the Florida Department of Transportation (FDOT). Surges generated by the lightning can enter the TTMS equipment through any one of the wires entering the equipment cabinet. Telephone lines are particularly vulnerable to lightning surges due to their long lengths offering greater opportunity for induced or direct strike surges. Historically, the FDOT has used surge suppressors to mitigate all but the most severe surges from damaging the modem and other equipment in the TTMS cabinet. These surge suppressors have been successful at protecting the equipment, but the suppressors have often been damaged or destroyed by these surges. Replacing the surge suppressors is expensive, especially in terms of manpower, and the TTMS data cannot be collected until the suppressor has been replaced.

The FDOT tasked the Electrical and Computer Engineering Department of the Florida A&M University-Florida State University (FAMU-FSU) College of Engineering with the task of determining the appropriate specifications and test procedures for identifying surge suppressors that will protect the equipment in the TTMS cabinets from telephone line surges, and will be resilient to surge suppressor failures. Dr. Bruce A. Harvey directed the efforts. The projects began with analysis and testing to determine the telephone line surge environment experienced by the TTMS sites. Failed surge suppressors were examined and tested to determine the mode of failure. It was discovered that the older suppressors were basically fuses that blew when exposed to high currents to protect the equipment. This was effective protection, but resulted in significant suppressor failures and expensive replacement costs. Newer suppressors used were based on gas tubes that allowed the surge currents to arc across a small gap and be dissipated to ground. These suppressors rarely failed, and when they did it was often due to causes other than surges (e.g. ants in the suppressors). Only a few of the suppressors had the physical damage expected from the apparently rare direct lightning strike.

To further quantify the lightning surge environment, hand-held data logging meters were installed in a few TTMS sites. These meters were able to log the time and peak voltage of surges entering through the telephone lines. The results from these tests demonstrated that some TTMS sites are experiencing a large number of surges. One particular site averaged 48 surges per day over the length of the test. The results from these field tests and the analysis of the failed suppressors indicated that the suppressors were not typically experiencing excessively large surges such as a direct lightning strike. The conclusion is that the surge suppressors for telephone lines need to be able to withstand large numbers (>1000) of significant surges (1000's of amps) while clamping the maximum voltage output to the modems to the range of 200-300 volts. This clamping voltage range is above the telephone ring voltages normally found on a telephone line and low enough to be reasonably certain that the surges will not damage the modems.

The second phase of the effort was to test existing surge suppressors using a surge generator. The goals from these tests were to determine the resistance of the suppressors to failure, to develop specifications for future telephone line surge suppressors, and to develop test procedures to validate the specifications. A surge generator was acquired for these tests with the capability to generate current surges up to 6000 Amps (IEEE standard 8/20 μsecond surges). Testing was performed on surge suppressors acquired or borrowed from EDCO, Citel and Surge Suppression, Inc. Also, a surge protector designed specifically for the FDOT by Thomlinson Instruments and Controls, Inc. was tested. The EDCO and Citel suppressors used gas tubes as their primary means of dissipate the surge currents. The designs of the Surge Suppression devices were proprietary, but the specifications referred to metal-oxide varistors (MOVs) as the primary elements of the devices. The Thomlinson surge protector was based on MOVs and a choke coil (inductor).

All of the surge suppressors were subjected to current surges of magnitude 6000 Amps without complete failure. Measurements of the output waveforms indicated that the output voltages of the gas tube-based devices shunted the output voltage to below 100 Volts by about 10 microseconds (μsec). The MOV-based Surge Suppression devices required about 30 μsec to shunt the voltage to below 100 Volts. Also, the output voltage waveform varied as the number of surges increased (not an unexpected result for MOVs), but the changes would not likely affect the protection offered by the devices. The Thomlinson surge suppressor required over 40 μsec to shunt the voltage below 100 Volts, but it was the only suppressor that eliminated the initial high-voltage spike on the output of the suppressor. The peak voltage output recorded on the output of the Thomlinson surge suppressor was less than 200 Volts.

Endurance tests were conducted on each type of telephone line surge suppressor. A total of at least 10,000 surges of 6000 Amps were attempted on each suppressor. The EDCO suppressor and the Surge Suppression S-D140-2X showed no deterioration during the tests. The output voltage waveform did not vary significantly and no physical damage was observed. Both Citel surge suppressors suffered some damage during testing. The damage was limited to connections at the suppressor inputs underlining the need for solid connections on the suppressors. The Surge Suppression S-TC-2 telephone line suppressor failed in less than 1,500 surges with obvious damage to the underlying components. The Thomlinson surge suppressor failed between 3000 and 4000 surges when one of the MOVs was physically destroyed.

From the tests undertaken, it is apparent that a gas tube-based surge suppressors offer the best protection and are among the most reliable of the available surge suppressors. From the environmental tests that were run, it was shown that it is not one big surge that is killing the surge suppressors, but a number of small ones. Therefore it is appropriate to acquire lower rate suppressors that can withstand a large number of surges that a higher rated one that is not resilient enough to withstand a large number of the small surges.

The following are the recommended telephone line surge suppressor specifications:

1. Peak Surge Capability: minimum of 10,000 Amps
2. Resiliency: 10,000 surges of magnitude 6,000 Amps (IEEE 8/20 μsec waveform)
3. Maximum Operating Voltage: 150 – 200 Volts
4. Clamping: Output Voltage clamped to below 200 Volts within 10 microseconds
5. Potting: The electronics contained in the surge suppressor should be potted, sealed in epoxy or otherwise sealed.

6. Connectors: Telephone Line Side: Solid mechanical connectors such as spade lugs with washers.
   Modem Side: RJ-11 modular telephone line jack and minimum 5' RJ-11 cable for connecting to the modem.

Specifications #1 and 3 can be met by the ratings of the suppressors. Tests were developed to determine if the suppressors meet the resiliency requirements of Specification #2. Specification #4 can be verified by capturing the voltage waveform on a storage oscilloscope during the resiliency testing.

1. INTRODUCTION

The Florida Department of Transportation (FDOT) has a number of Telemetered Traffic Monitoring Sites (TTMS) that collect data from Florida's highways. These sites encounter a number of lightning surges through the telephone lines and in-pavement sensors. These surges are especially prevalent during the summer months when the thunderstorm activity in Florida is at its peak. A lightning surge can disable a TTMS site if it damages the equipment used for measurement or communication. Surge suppressors are used to protect the equipment from damage due to lightning surges. The surge suppressors are designed to protect the equipment at "all cost" including destruction of the surge suppressors. Unfortunately, the TTMS site must be repaired even if the surge suppressors fail while successfully protecting the TTMS equipment. Recent experience with the telephone line surge suppressors, in particular, have shown that some suppressors fail too often requiring frequent visits by FDOT and contract personnel to replace the suppressors. The focus of this research project was to determine the causes of failure and recommend specifications for future telephone line surge suppressor acquisitions.

The telephone line surge suppressors manufactured by EDCO and CITEL are currently the primary brands in use by the FDOT at the TTMS sites. The models and types of suppressors have varied over the recent years with widely varying reliability and longevity in the field. The thrust of this research was to determine why a number of them were failing at a high rate and whether there was anything that could be done to slow down the rate of failure by these devices. The first task undertaken was to quantify the surge environment experienced at the TTMS sites; in particular to determine whether it was one surge killing the surge suppressors or a number of small surges. To that end, the following steps were taken:

- Analysis of failed surge suppressor units and
- Identification of the lightning environment.

The results of the study of the lightning surge environment led to laboratory tests to measure the resilience of currently available surge suppressors. The results of these efforts were used to develop recommended standards and acceptance test procedures for telephone line surge suppressors.

2. LIGHTNING ENVIRONMENT

The state of Florida often referred to as the lightning capital of North America (see Figure 1 for a lightning flash density map for the 48 contiguous states). Telephone lines are vulnerable to currents induced by nearby lightning strikes in addition to the less frequent direct strikes. Thus telephone equipment in this state needs to be well protected by surge suppressors to reduce the risk of equipment damage and subsequent data loss. These suppressors take the most, if not all, of the large currents and shunt them to ground, in effect protecting the equipment from unwarranted currents. Sometimes the suppressors are damaged by the large currents and must be replaced. The investigation undertaken was to determine whether the suppressors were failing due to induced currents in excess of their rated limits, or due to numerous smaller surge currents that cause the devices to "wear out." To that end, two steps were undertaken with the first step being the investigation and analysis of the failed surge suppressors and the second step involving the field measurements to determine the telephone line surge environment experienced by the TTMS sites.

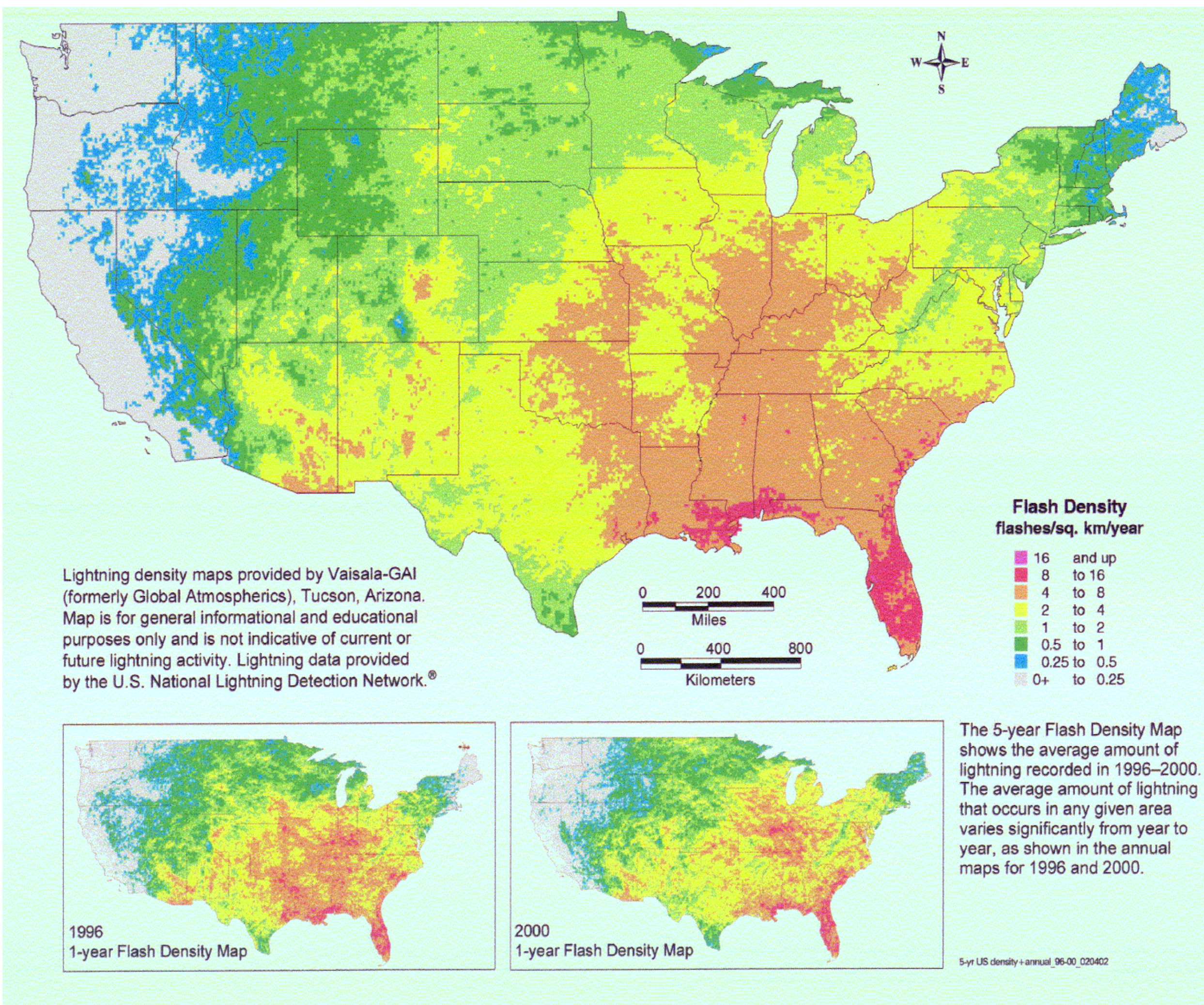


Figure 1. Lightning Density Map for the United States

2.1. Analysis of Failed Surge Suppressors

A number of failed surge suppressors were provided by the FDOT. These suppressors were removed from TTMS sites because they appeared to be not functioning. Each of the suppressors was disassembled and the cause of failure was determined through visual inspection and testing of the individual devices within the suppressor.

All the surge suppressors analyzed were the EDCO FASTEL DOT surge suppressors, however, the surge suppressors were not all the same. The first batch of suppressors to be tested was a group of older suppressors that had been removed from TTMS sites around 1995-1996. These suppressors consisted of 2 fuses followed by a solid state voltage limiter called a sidactor (see Figure 2). The later batch of surge suppressor analyzed looked identical from the outside, but when the cover was removed it was found that the internal components included a 3-terminal gas tube (left in Figure 3), 2 resettable fuses (yellow) and a sidactor. Apparently, the newer design replaced the older at some time in the last 5 years.

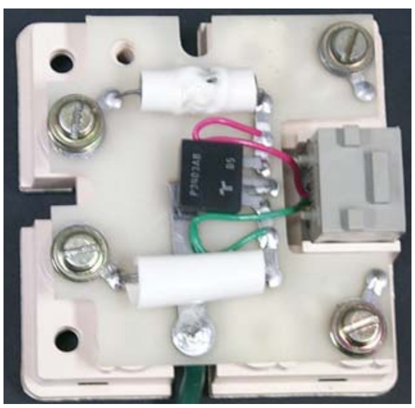


Figure 2. Older EDCO Suppressor

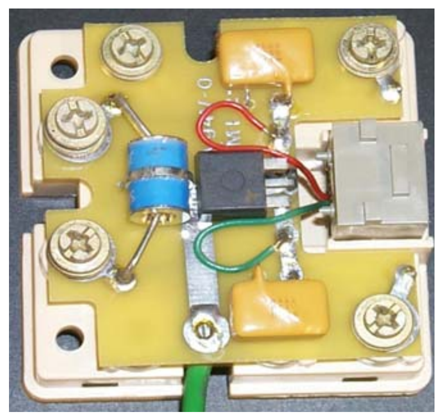


Figure 3. Newer EDCO Suppressor

Analyses of suppressors with fuses found, not surprisingly, that the fuses were the primary cause of failure. The fuses were mostly non-functional and in most of the cases had obvious physical damage or were completely destroyed. Table 1 lists the cause of failure for each of the older EDCO suppressors analyzed. This table shows that a little over 75% of the suppressor failures were due to the fuses.

Analysis of the newer variant of the EDCO suppressors removed from the TTMS sites for apparent failure was very interesting. None of the internal components were damaged or non-functional in the newer EDCO suppressors analyzed. The only potential cause for apparent failure was insect infestation.

Table 1. Older EDCO Surge Suppressor Failure Analysis

Site Number	Reason for Failure	Date of Failure
0	3	
0	3	
0	4	
0	3	
0	3	
0	4	
54	1	6/4/96
102	3	6/13/96
109	3	9/27/95
116	5	6/5/96
128	3	9/27/95
152	3	
161	5	6/14/01
219	2	4/10/96
229	4	11/16/95
236	3	8/28/95
250	3	10/9/95
251	2	8/21/95
252	2	11/2/95
254	1	10/17/95
254	3	
254	4	8/14/96
282	4	10/31/95
291	2	8/7/95
291	3	8/30/95
310	3	6/13/96
913	3	8/22/95
927	3	8/23/95
7904	3	8/8/96

1. Minor Physical Damage to Fuse
2. Major Physical Damage to Fuse
3. No Physical Damage but Fuse "gone"
4. Nothing wrong with Fuse
5. Short Circuit with sidactor

NOTE: % of Suppressors that fail due to problems with the fuses was **75.862%**

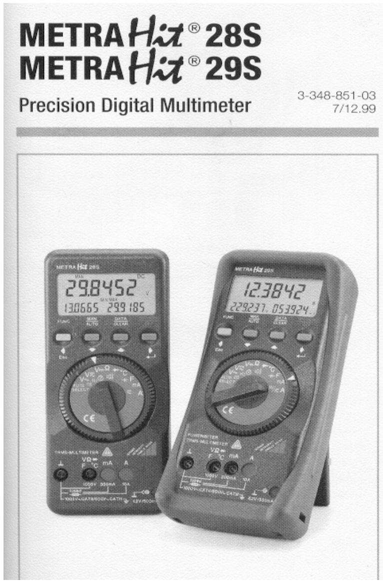
2.2. Field Experiments to Determine Surge Environment

The "failed" surge suppressors analysis described in the previous section seemed to indicate that significant surges were occurring on the telephone line, but that direct lightning strikes were rare. However, the number of surges experienced by the suppressors could not be determined from this sort of post mortem investigation. Therefore, the next phase of the research was to attempt to quantify the lightning surge environment through direct measurement.

Two MetraHit 29S hand-held data-logging meters (see Figures 5 and 6) were purchased. These meters were designed to be used to measure and record over and under voltage events on electrical power systems. By adjusting their trigger thresholds these meters were able to detect surges on a telephone line. The units were installed at the TTMS sites detected voltages above the normal required voltages (50 Vdc + 90 Vac). The unit setup involved connecting one probe to the gas tube of the surge suppressor and the other end of the probe to ground (see Figure 7). The MetraHit 29S can record pulses ≥ 5 μSec and > 200V, the minimum threshold setting. Not only can the meter store pulses with magnitude, but also records the date and time. Collecting this data can provide a clearer picture of the lightning environment at the TTMS sites, particularly whether the sites are experiencing an occasional extremely large current surge or a large number of smaller surges.

Two MetraHit 29S meters were purchased and were tested in three sites in the state of Florida. These sites were:

- Site 245:
  State Highway 59 just north of US 27, south of Lloyd in Jefferson County
- Site 192:
  State Highway 20 just west of US 231, north of Youngstown in Calhoun County
- Site 906:
  Interstate 4 near Deltona in Volusia County



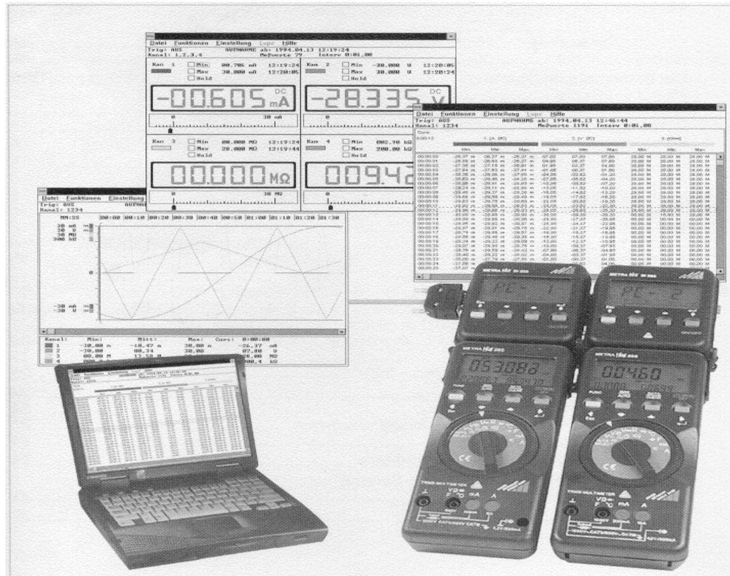


Figure 5. MetraHit Multimeter **Figure 6. MetraHit Multimeter and Software**

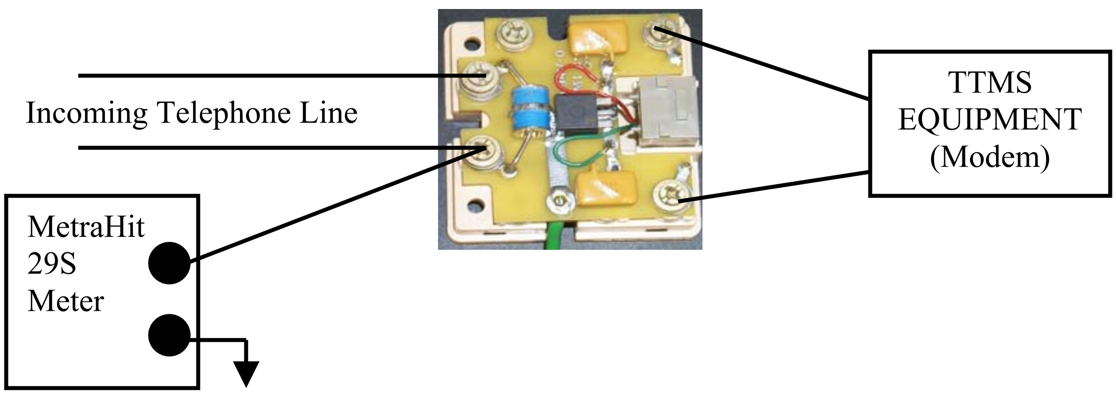


Figure 7. MetraHit Meter Setup

The internal batteries of MetraHit meters did not have sufficient capacity to operate the meters for the length of time necessary for a meaningful test (hours instead of days). Therefore an external 4.5 Volt power supply was needed to supply the meters. Voltage regulators were purchased to obtain 4.5 Volts from a 12 Volt battery supplied by the FDOT. A separate 12 Volt battery was installed to power the meters during testing to avoid excessive loading of the TTMS site battery. A typical 12 Volt battery used by the FDOT was found to supply a MetraHit 29S for over 1 month.

2.3. Surge Measurements

As mentioned previously, the field tests took place in three areas of the state. These areas were Highway 59, Highway 20 and Interstate 4; sites 245, 192 and 906, respectively. The maximum voltage and the time/date of each surge were recorded. From this data, daily surge count summaries were generated. These surge summaries are included in Appendix B.

Site 245 on Highway 59 (Lloyd) was monitored for thirty-seven days (6-28-01 to 8-03-01). From this site, there were a total of twenty-six surges. On 6-29-01 the site had a peak of nine surges occurring. Reviewing the data indicated that some of the surges were not single impulses of current, but rather a rapid alternating sequence of positive and negative current surges commonly referred to as ring surges. These types of surges can have causes including the alternating nature of the lightning bolt and the natural resonance of a long wire. Of the 26 surges measured at site 245 nine of them were ring surges. Site 245 was used to test the measurement techniques. The site was not historically vulnerable to surge suppressor failures, but was conveniently located near Tallahassee.

Site 192 on Highway 20 (Youngstown) was monitored for ninety-two days (7-03-01 to 10-02-01) and had a total of 4,460 surges including 556 were ringing surges. This site had an average of over 48 surges per day, yet the surge protector at the site (EDCO FASTEL DOT with the gas tube) never failed. The site had a peak of 461 surges occurring on 8-16-01 and several other days with over 100 surges recorded. During these tests tropical storm Barry passed near this site and impacted the weather for three days, 8/5/2001 – 8/7/2001. During this period there were no surges recorded. This was expected since Barry produced considerable rainfall but produced practically no thunderstorms in the area.

Measurements were attempted at a third site, site 906 on Interstate 10 near Deltona. This site has historically had a high number of lightning related failures. Two attempts were made to record surge counts at this site. The meter was installed and left for a few weeks and then the data was extracted from the meter. Each time, the data covered only about 2 days of information and the memory in the meter was full. The meter with data was returned to the manufacturer and it was determine that the voltage on the telephone line appeared to be dropping unexpectedly and it triggered the under-voltage detection feature of the meter. These measurement events filled the meter's memory ending the measurements after 2 days. A threshold was adjusted to prevent the triggering of under-voltage, but by that time the peak lightning season in Florida had ended and the tests were not repeated. The results of the tests at this site were only 4 days of measurement. Three of the days had no surges, but on one day 90 surges, including 3 ring surges, were recorded. Extrapolating these measurements (a potentially questionable practice) indicates that this site experiences surges on the same order of magnitude as site 245. Note that the testing at site 906 was conducted over a period of almost 2 months of the peak lightning season in Florida and the surge suppressor in the unit (again an EDCO FASTEL DOT with gas tube) did not fail over this time.

The results acquired from the data loggers set up at these sites indicate that these sites are experiencing large numbers of surges. These surges are likely to be indirect currents caused by the electromagnetic fields around lightning strikes in the area. The physical size of the surge suppressors cannot possibly protect the equipment and survive a direct lightning strike, but this is expected to be a rare event. The conclusion is that to be effective, the surge suppressors for telephone lines need to be able to withstand large numbers (>1000) or significant surges (1000's of amps) while clamping the maximum voltage output to the modems to the range of 200-300 volts. This clamping voltage range is above the telephone ring voltages normally found on a telephone line and low enough to be reasonably certain that the surges will not damage the modems.

3. LABORATORY TEST PHASE

With the information acquired in the surge measurement phase some candidate telephone line surge suppressors were collected for testing. Four different telephone line surge suppressors were purchased or borrowed for testing. In addition, two data line surge suppressors were available and tested as well. The surge suppressors tested are listed in Table 2. Table 2 also includes the primary technology (device) used for surge suppression and the types of connectors available on each suppressor.

Data sheets for all the surge suppressors except the Thomlinson suppressor are provided in Appendix C. The Thomlinson suppressor was not made available commercially and has no data sheet. More information can be found in the project final report "Lightning Protection for Telemetered Traffic Monitoring," WPI No. 0590383, Job No. 99990-1560, Contract No. C4097.

Table 2. Surge Suppressor for Laboratory Testing

Manufacturer	Model Number	Type	Technology	Line Connector	Modem Connector
EDCO	FASTEL-FDOT	Telephone	Gas Tube	Terminals	RJ11 (modular) or Terminals
Citel	BP1-T	Telephone	Gas Tube	RJ11	RJ11
Citel	B180T MJ6	Telephone /Data Line	Gas Tube	Terminals	Terminals
Surge Suppression	S-TC-2	Telephone	MOV	Terminals	Terminals
Surge Suppression	S-D140-2X	Data Line	MOV	Terminals	Terminals
Thomlinson	T-4938	Telephone	MOV / Choke Coil	Terminals	Terminals

The FDOT is currently using primarily the EDCO FASTEL and Citel BP1-T surge suppressors. The data sheets provided did not state the resiliency of the suppressors to multiple surges. The manufacturers were contacted and were requested for the surge suppressor ratings with respect to number of current surges their suppressor can endure. Juan Carlos Rodriguez from Citel provided the following ratings for the Citel surge suppressors.

The Citel specified surge ratings are:

BP1-T	10 times at 10,000 Amps 100 times at 5,000 Amps 500 times at 3000 Amps 1000 times at 1000 Amps
B180T MJ6	1 time at 10,000 Amps 10 times at 5,000 Amps 100 times at 3,000 Amps 500 times at 1,000 Amps

EDCO was also contacted and the surge ratings provided (by Kevin) were:

EDCO FASTEL	10 times at 10,000 Amps 100 times at 2,000 Amps

With these specifications, surge suppressors were purchased from EDCO and Citel with the aim of finding out whether they met specifications or not.

The two surge suppressors from Surge Suppression, Inc. were donated and added to the tests to broaden the test to include other suppressors not currently used by the FDOT. The two surge suppressors donated were the S-TC-2 and the S-D140-2X. The S-TC-2 is a telephone line surge suppressor comparable to the Citel and EDCO suppressors tested. The S-D140-2X is a data line surge suppressor and is not used for telephone line surge suppression (it was added to the test due to availability). The designs of these suppressors are proprietary, but the company web pages refer to their metal-oxide varistor (MOV) technology.

The Surge Suppression, Inc. specified surge ratings (from data sheets) are:

S-TC-2	30,000 Amps (repetition not rated)
S-D140-2X	10,000 Amps (repetition not rated)

Finally a sample of the surge suppressor designed by Thomlinson Instruments and Controls (model T-4938) was provided by the FDOT. There was no specific rating for the suppressor as a whole, but the individual metal oxide varistors (MOVs) used in the design is rated for 6500 Amps.

To test these suppressors, a MIG 0606 impulse generator (see Figure 8) was purchased from EMC Partner in Switzerland. The generator had the capability of providing 250 to 6000A (8/20 μSec) current surges. The 8/20 μSec format implies that it takes 8 μSec for the waveform to reach its peak and 20 μSec for the waveform to reach half it maximum peak while descending. For more information on the 8/20 waveform and standard testing of surge suppressors refer to following Institute of Electrical and Electronics Engineers (IEEE) standards:

- "Draft Standard Test Methods for Surge Suppressors Using in Low-Voltage Data, Communications, and Signaling Circuits," PC62.36, July 1999.
- "IEEE Guide for the Application of Gas Tube and Air Gap Arrester Low-Voltage (Equal to or Less than 1000 Vrms or 1200 Vdc) Surge-Protective Devices," C62.42, 1992.

- “IEEE Standard Specifications for Surge Protectors Used in Low-Voltage Data, Communications, and Signaling Circuits,” C62.64, 1997.

The tests were designed to verify the suppressor ratings and specifications provided. Also, the tests were designed to provide an initial assessment of the resiliency (durability) of the suppressors exposed to large numbers of high-current surges. The test set-up and procedures can be viewed in APPENDIX D. During the test phase, voltage and current waveforms for the devices were taken and these can be viewed in APPENDIX A.

Figure 8. Impulse Generator

3.1. Preliminary Testing

Some preliminary tests were performed on the EDCO and Citel surge suppressors. These tests were intended to gain familiarity with the surge generator and to clarify the test methodology. These tests however did provide some information useful to this research.

The first useful information came from the first tests with the EDCO FASTEL DOT surge suppressors. The connectors (red and black in Figure 8) from the surge generator were connected to one telephone line input and the ground connector of the surge suppressor. Initially the peak voltages appeared to be correct, but repeated tests revealed a rapidly increasing peak voltage. Also, the volume of the sound produced by the surge increased dramatically. A physical inspection of the suppressor revealed that the surge pulses had destroyed the conductor on the circuit card (see Figure 9). The voltage and sound volume increases had been due to the surge current arcing from the input terminal screw to the lead on the gas tube. An examination of the connection to the input terminal of the suppressor revealed that the connecting wire had been place under the 2 washers (between the washers and the circuit card) rather than between the washers. This resulted in a weaker connection generating heat and arcing that destroyed the circuit card conductor. The lesson learned is that the connections to the surge suppressors need to be secure and between the washers to prevent damage to the suppressors.

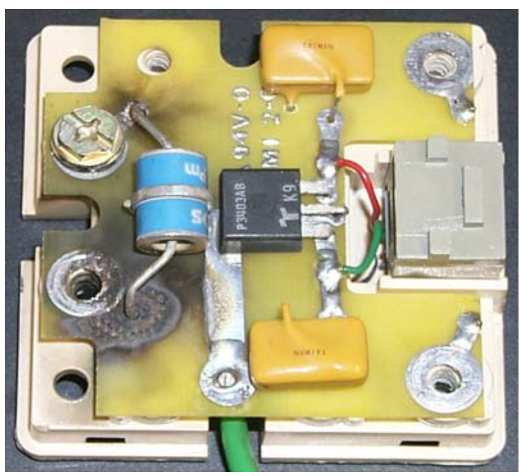


Figure 9. Burned Pads for EDCO

The second piece of useful information came from the initial tests of the Citel B180T MJ6 surge suppressor. During these tests the surges introduced to the suppressor were conducted in the line-to-ground configuration (as mentioned in the EDCO test above) and in the line to the other (line-to-line) configuration. In both configurations, surges of 6000 Amps severely damaged the modular telephone connector (RJ11) on the input (see Figure 10) on the first surge. The large current destroyed the contact leads making the suppressor lose connection with the input telephone line.

The damage seen on the inputs of the EDCO and Citel suppressors were both due to poor or small contacts that were damaged by the large surge currents. In later endurance tests, the Citel B180MJ6 failed due to current damage at the contact between the terminal strip and the circuit card (see Section 3.3). The primary lessons learned include (1) the suppressors should be designed with very solid connections that can be physically tightened (i.e. a screw terminal) and not modular connectors (RJ11) commonly used for telephones and modems; and (2) if a separate terminal strip is used, it should be mounted securely to allow firm tightening of the connection, and should also be well connected to the circuit board with a tightened or soldered connection.

Figure 10. Citel B180MJ6 Suppressor with Damaged Connector

It is reasonable to assume, based on electromagnetic principles, that most lightning surge current induced on a telephone line will be approximately the same for both wires in the telephone line local loop. Therefore, the primary surge will be a current coming in through each line and dissipating to ground. The field surge measurements (Section 2) verify that large voltages can be measured line-to-ground during lightning surges. Also, it is reasonable to assume that since the induced currents are equal on the two telephone line conductors there will be less voltage potential between the wires (line-to-line) than line-to-ground. Thus the primary surge currents to be tested are the line-to-ground currents. All remaining tests performed on the surge suppressors were performed line-to-ground.

3.2. EDCO Tests

The EDCO FASTEL DOT surge suppressors consist of three main types of components. These components are a gas tube, a solid-state silicon device and two resettable poly-switches (see Figure 3). A large number of tests were run on the EDCO surge suppressors. First, the surge current was increased from 500 Amps to 6,000 Amps to determine if the suppressors failed at a current surge lower than the rated limits. During these tests an oscilloscope was used to monitor the output voltage and verify the specified clamping voltage. During these tests, none of the EDCO surge suppressors failed and the clamping voltages remained within specified values. After each test, the suppressors were tested using a telephone line emulator and modem to see if they were still functioning (see Figure 11). After the telephone line emulator test, the suppressors were also placed between a phone line and a telephone (see Figure 12) and a phone call was placed. All suppressors functioned properly.

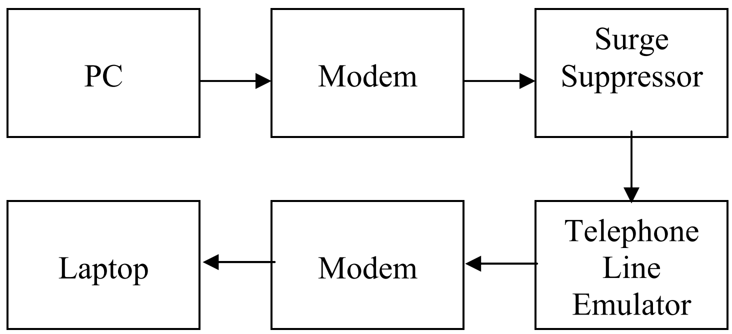


Figure 11. TLE Setup.

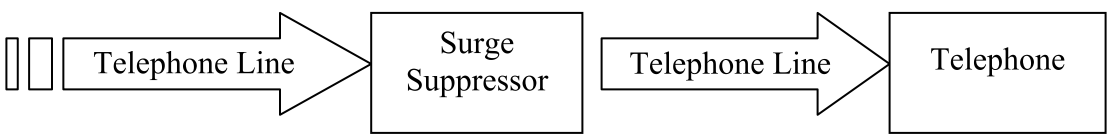


Figure 12. Telephone Line Setup

Surge tests were conducted on the EDCO FASTEL DOT suppressor to determine its resilience to large numbers of surges. Since the EDCO suppressor does not have a typical modular telephone line connector on its input, line-to-line tests were performed in addition to the standard line-to-ground tests. For the line-to-line test, the EDCO FASTEL DOT took 500 hits at 6000 Amps and was functioning after running it through the TLE and the phone line tests. In respect to the line to ground tests, the EDCO FASTEL DOT endured 4,920 hits at 6000 Amps and was still functioning when it was run through the TLE and the phone line tests. For long-term endurance testing, the suppressor was also subjected to 10,000 line-to-ground surges at 6000 Amps. There was no perceptible damage or change in performance of the suppressor. The EDCO surge suppressors tested exceeded their rated limits (100 surges at 2000 Amps) considerably without failing.

3.3. Citel Tests

Two CITEL surge suppressors were tested during this phase. These were the BP1T and the B180 MJ6 (see Figures 13 and 14). The BP1T is a telephone line suppressor, while the B180 MJ6 is a data line suppressor. The B180 MJ6 operates for voltages up to 180 Volts making it also suitable for telephone line surge suppression.

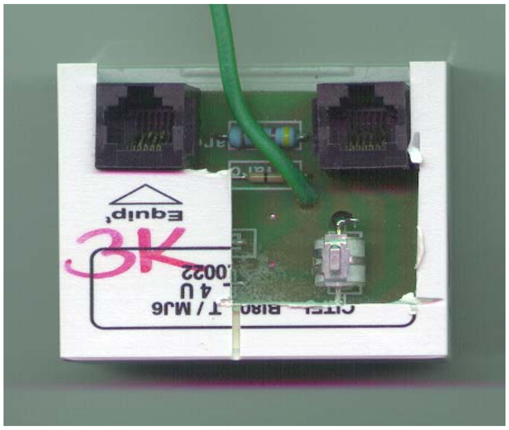


Figure 13. CITEL BP1T

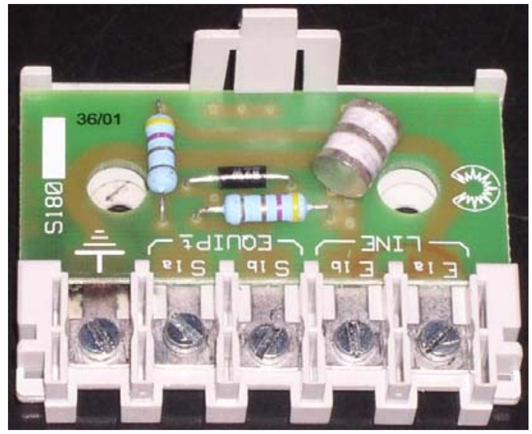


Figure 14. CITEL B180 MJ6

The BP1T was tested with line-to-ground tests with currents of 1000 and 6000 Amps. To bypass the connector damage discovered in Section 3.1, a separate wire was soldered to the gas tube within the suppressor to conduct these tests. Thus the components on the circuit card can be tested separate from the problems associated with the modular connector. The 1000 Amps surges were applied 2000 times. After the 2,000 surges, the TLE and phone line tests were administered and the suppressor was still in working order. A total of 11,100 surges at 6000 Amps were applied to the suppressor. No physical damage was noted and the suppressor was still functioning.

The B180MJ6 was tested with line-to-ground surges of 3000 Amps initially. A total of 800 hits were administered at 3000 Amps. After taking those hits, the TLE and phone line test were administered and the suppressor was still working. For long-term endurance testing, the suppressor was also subjected to 10,000 line-to-ground surges at 6000 Amps. After 9,700+ surges the surge generator detected large input voltages (over 2000 V) and stopped the test. It was found that the terminal lugs were connected to the circuit board by a simple contact with an etched pad on the circuit card (as opposed to soldered connections or connections that can be tightened with a bolt). The surge currents had destroyed the contact points as seen in Figure 15. For greater endurance a more solid connection to the circuit card is recommended.

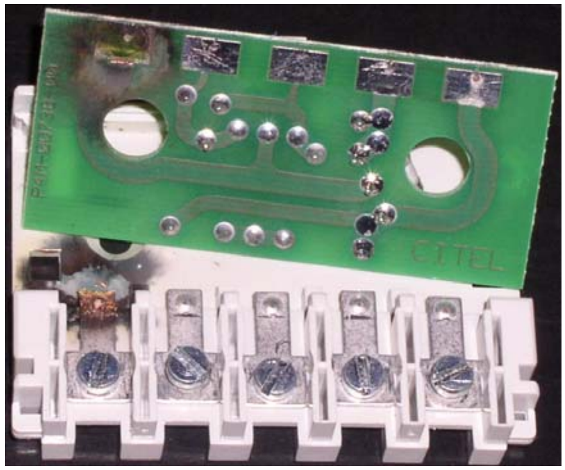


Figure 15. Citel B180MJ6 Damaged by Endurance Test

3.4. Surge Suppression, Inc. Tests

Two surge suppressors from Surge Suppression, Inc., the S-TC-2 (See Figure 16) and the S-D140-2X (See Figure 17), were tested. These suppressors reportedly use MOV (metal oxide varistor) technology compared to the other suppressors from CITEL and EDCO that use gas tubes. MOVs are solid-state shunt surge protective devices made of a ceramic compound consisting of ZnO (Zinc Oxide) granules. According to a technical note from Northern Technologies Incorporated, MOVs are known to degrade based on the amount of energy they absorb. With degradation, comes the reduction of the clamping voltage leading to failure of the MOVs when the structures clamp voltage reaches the peak voltage of the AC sine wave. In the Instruments and Electronics conference paper titled *Metal Oxide Varistors as Surge Suppressors (pp 445 – 449)* written by V.P. Rabade, the theoretical response time for the varistor is less than 0.5 nsec while the practical response is about 30 nsec. This, according to V.P. Rabade, is attributed to the parasitic inductance of the package and the leads. Thus, if the response time is about 30 nsec, one has the equipment taking in more current in effect causing a higher probability of equipment failure thus rendering the surge suppressor useless as it has let through the current it is required to prevent.

Figure 16. Surge Suppression S-TC-2 **Figure 17. Surge Suppression S-D140-2X**

The S-TC-2 is a telephone line surge suppressor while the S-D140-2X is a data line surge suppressor. No information was provided from the manufacturer concerning the design or components within the suppressors. Investigations using a simple ohmmeter determined that the inputs were directly connected to the outputs, and that one side of the circuit (one input-output pair) was directly connected to physical ground. Therefore, the circuit must be connected carefully with the proper (negative) side of the phone line connected to ground. Also, the results indicate that the suppression devices must be connected in such a manner as to shunt the ungrounded side to ground when a lightning surge occurs. Given that MOVs tend to fail in such a manner as to leave the connection open, this would leave the connected equipment (modem) able to communicate on the phone line, but unprotected from future lightning surges. In contrast, gas tube suppressors theoretically fail by creating a short that would disable the modem's ability to communicate, but will protect the modem from future surges. Tests were performed on each of the Surge Suppression, Inc. suppressors by applying the surge current to the ungrounded input.

Initial tests run on each of the suppressors were: 30 hits each at 250A, 500A, 1000A, 1500A, 2000A, 2500A, 3000A, 3500A, 4000A, 4500A, 5000A, 5500A and 6000A. These tests were performed in this manner in order to determine the amount of degradation or variance in parameters that occurs with large numbers of surges. All in all, 390 hits were administered on each of the surge suppression surge suppressors. The results showed that the output waveform did indeed vary as a function of the number of surges experienced. Initially, the output voltage waveforms were broad (10's of microseconds) with no evident plateau or clamp level less than 300 Volts. After a total of 390 surges the output waveforms showed a definite plateau or clamping voltage, but this level remained above the minimum clamping voltages acceptable for telephone line use. Thus the MOV's did appear to change characteristics, but this change did not cause the suppressors to cease functioning properly.

Input and output voltages during 6000 Amp surges were plotted for the S-TC-2 and can be found in Appendix A. Although on different scales it can be seen that the plots are essentially identical, as expected. The input voltage waveform for a 6000 Amp surge of the S-D140-2X is also included in Appendix A.

Next, the S-TC-2 and S-D140-2X suppressors were each subjected to repeated 6,000-Amp surges. The S-TC-2 was initially subjected to 1,492 surges. At some point during the surges a failure occurred resulting in the cover of the unit buckling. The cover screws were removed and the cover was lifted slightly (the cover could not be removed as the interior components were sealed in some form of resin). A visual inspection revealed damage that appeared to physically destroy one or more of the MOVs. However, the input-output connections of the suppressor were intact and a modem could still communicate through the suppressor.

The S-D140-2X suppressor was tested with 11,350 surges of 6000 Amps. The suppressor was not damaged by the surges and the output characteristics remained stable. The unit was sealed and thus no physical inspection of the internal components was conducted.

3.5. Thomlinson Surge Suppressor Tests

A T-4938 surge suppressor developed under an FDOT contract by Thomlinson Instruments and Controls was obtained from the FDOT for testing (See Figure 18). This suppressor was built primarily using MOV technology, but also included a choke coil that suppresses rapidly changing currents.

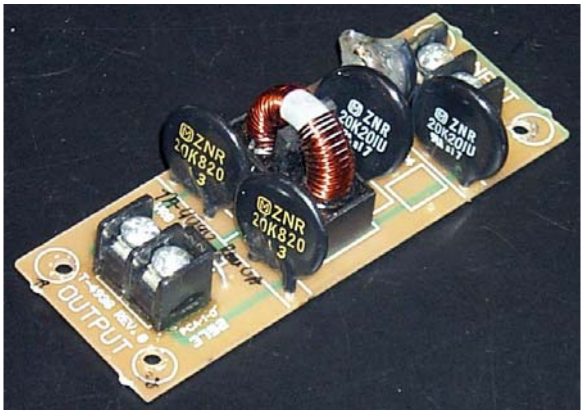


Figure 18. Thomlinson T-4938 Surge Suppressor

The Thomlinson surge suppressor was subjected to increasing surges from 250 Amps to 6000 Amps without failure. One promising result of the testing was evident when the output waveform was viewed (see Appendix A). Even at 6000 Amps, the output voltage never exceeded 200 Volts. Each of the other tested suppressors allowed brief (up to 10's of microseconds) pulses of voltages higher than 300 volts on the output. The reason for the lack of the high-voltage spike on the Thomlinson suppressor output can be attributed to the choke coil. The choke coil inhibits rapid current changes, thus reducing the surge current effects on the output.

The endurance of the Thomlinson suppressor was tested by subjecting the suppressor to multiple 6000 Amp surges (line-to-ground). Between the 3000th and 4000th surge, a MOV on the Thomlinson suppressor was destroyed (See Figure 19). This suppressor had the least resilience of the suppressors tested (not including physical connector failures on the Citel suppressor.

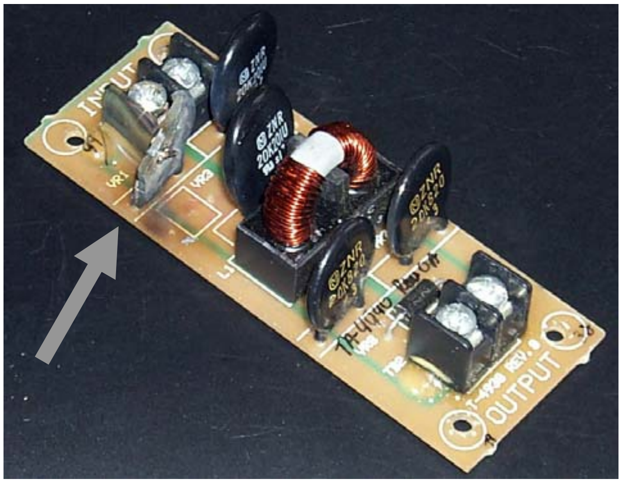


Figure 19. Thomlinson Suppressor with Failed MOV

3.6. Test Conclusions

From these tests, it was concluded that the gas tubes are more resilient than the fuses as the end results (see Figures 20 and 21) show. These figures show the EDCO surge suppressors after they have been hit with 6000A.

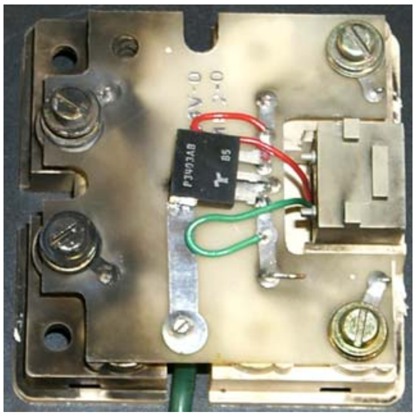


Figure 20. EDCO Suppressor with Fuse

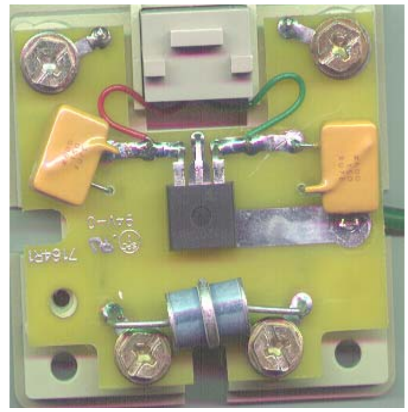


Figure 21. EDCO Suppressor with Gas Tube

The question as to why the fuse failed and the gas tube remained to see another day could be attributed to the fact that fuses are generally designed to sacrifice themselves after one big hit while the gas tube on the other hand can take multiple hits at 6000A and still function. The newer surge suppressors from EDCO and CITEL have three devices. These three devices are basically the gas tube, which happens to be the most resilient, the reset-table fuses and the sidactor. The sidactor, which is basically the silicon voltage limiter is the fast switching device (< 1ηSec) and is the first line of defense and probably the weakest. The gas tubes generally take the brunt of the current coming through. The reset-table fuses are slow and are more to protect the equipment from improper wiring than anything else.

As to the number of hits taken, the EDCO (newer model with gas tube), and the Surge Suppression, Inc. S-D140-2X surge suppressors each survived over 10,000 surges at 6000 Amps. The internal components of the CITEL suppressors (both models) survived over 10,000 surges of 6000 Amps, but the connectors and electrical contacts failed. An older model EDCO suppressor with the fuse disintegrated on only one 6000 Amp surge. The S-TC-2 surge suppressor from Surge Suppression, Inc. was destroyed in less than 1,500 surges at 6,000 Amps.

The current EDCO FASTEL and the S-D14-2X appeared to perform very consistently independent of the number of surges experienced. However, the output plots of the S-TC-2 suppressor showed considerable changes as a function of the number of surges. The clamping voltages at the output of the S-TC-2 appeared to reduce as the number of surges increased. This is not in itself a problem, but is expected given that the S-TC-2 use metal-oxide varistors (MOVs) which are reported to have varying characteristics due to thermal effects.

At the conclusion of the 10,000-surge tests (or prior to suppressor failure), plots of the input and output voltages during 6000-Amp surges were generated. Appendix A contains the input and output voltage plots for each of the suppressors tested. The first diagrams are the V-CRO outputs from the current generator recorded on the oscilloscope (scale 1 Volt = 600 Volts) while the last diagrams are from the output of the surge suppressors that are directly measured by the oscilloscope. The Citel B180MJ6 and the Surge Suppression, Inc. S-D140-2X are data line surge suppressors, not telephone line suppressors, but their clamping and let-through voltages are sufficient for use on telephone lines. An interesting difference can be seen between output voltage plots of the gas tube suppressors (Citel and EDCO) and the output voltage plot of the MOV-based S-TC-2 suppressor. The gas tube devices and the S-D140-2X suppressor were capable of returning the output voltage to 100 Volts or below within 10 μseconds of the start of the surge. The S-TC-2 output voltage remained above 100 volts for over 30 μseconds. The S-TC-2, while meeting the clamping voltage requirements of the suppressor, actually allowed more power from the surge to reach the output device (modem) than did the other phone-line surge suppressors tested. This slightly increases the probability that the output device (modem) attached to the S-TC-2 will be damaged from a lightning surge as compared to using the other suppressors.

4. CONCLUSIONS AND RECOMMENDED SPECIFICATIONS

From the tests undertaken, it is a forgone conclusion that for the equipment to be sufficiently protected, it should have at least a gas tube present as part of the safety devices. From the environmental tests that were run, it was shown that it is not one big surge that is killing the surge suppressors, but a number of small ones. Therefore it is appropriate to acquire lower rate suppressors that can withstand a large number of surges that a higher rated one that is not resilient enough to withstand the small surges although it can take a big surge.

Recommended Specifications:

- Peak Surge Capability: minimum of 10,000 Amps
  Note: This is generally provided in vendor specifications. While the actual surge currents experienced in the field were not measured, reasonably priced suppressors with 10,000 Amp surge capabilities are readily available. Thus it is recommended that lower peak surge devices be avoided.
- Resiliency: 10,000 surges of magnitude 6,000 Amps
  Note: This should be tested as described in Appendix D. Specifications widely vary concerning maximum surge and maximum number of surges rated.
- Maximum Operating Line Voltage: 150 – 200 Volts
  Note: Clamping voltages closer to 150 V provide better protection. Some telephone line surge suppressors specify lower continuous operating voltages (130 V for the S-TC-2) that may not work on all phone lines due to triggering on the ring voltages.
- Clamping: Output Voltage clamped to 200 Volts or below within 10 microseconds.
  Note: The response time specified by many vendor (< 1 nanosecond specified by both EDCO and Surge Suppression, Inc.) seems to have little correlation with the measured clamping time. This should be tested.
- Maximum Dimensions: 6” × 6” × 6”
- Potting: The electronics contained in the surge suppressor should be potted, sealed in epoxy or otherwise sealed to avoid weather damage and insect infestation.
- Connectors: Telephone Line Side: Solid mechanical connectors such as spade lugs. Washers are recommended to improve contact.
  Modem Side: RJ-11 modular telephone line jack and minimum 5’ RJ-11 cable for connecting to the modem.

One of the most prevalent problems found during testing had to do with mechanical connections. Terminal strips are preferable for the telephone line side of the suppressor. Also, the terminals need to be securely connected (electronically and physically) to the circuit board or devices. Touch or small area contacts need to be avoided.

Finally, it is recommended that the suppressor provide protection for most scenarios of failure. For example, gas tubes are reported to fail by shorting (if not completely destroyed in a large surge). This is preferable to MOVs that are simply destroyed leaving a working modem connection, but no protection from further lightning surges.

APPENDIX A - TEST WAVEFORMS

This appendix contains plots of the input and output voltages recorded on each surge suppressor during 6000 Amp surges. These surges were recorded on suppressors after they had been subjected to at least 100 surges of 6000 Amps.

Figures A.1 through A.5 are the input voltages captured on an oscilloscope from the V-CRO output of the surge generator. Note that the V-CRO voltages are scaled to 1 Volt output = 600 Volts surge. These plots give a view of how quickly and at what voltage the suppressors begin absorbing the current from the surges. The plots are scaled to ½ Volt per division vertically and 5 μseconds per division horizontally.

Figures A.6 through A.10 are plots of the voltages at the outputs of the surge suppressors during 6000 Amp surge tests. These plots were captured directly with an oscilloscope with a scale of 50 Volts per division vertically and 5 μseconds per division horizontally. Note that for the Surge Suppression, Inc suppressors the input and output voltage are almost identical due to direct connections between them. This can be seen by examining the input (Fig. A.4) and output (Fig. A.9) plots for the S-TC-2 (and adjusting for the scale factors in each of the plots). Therefore, only the input voltages are provided for the S-D140-2X suppressor.

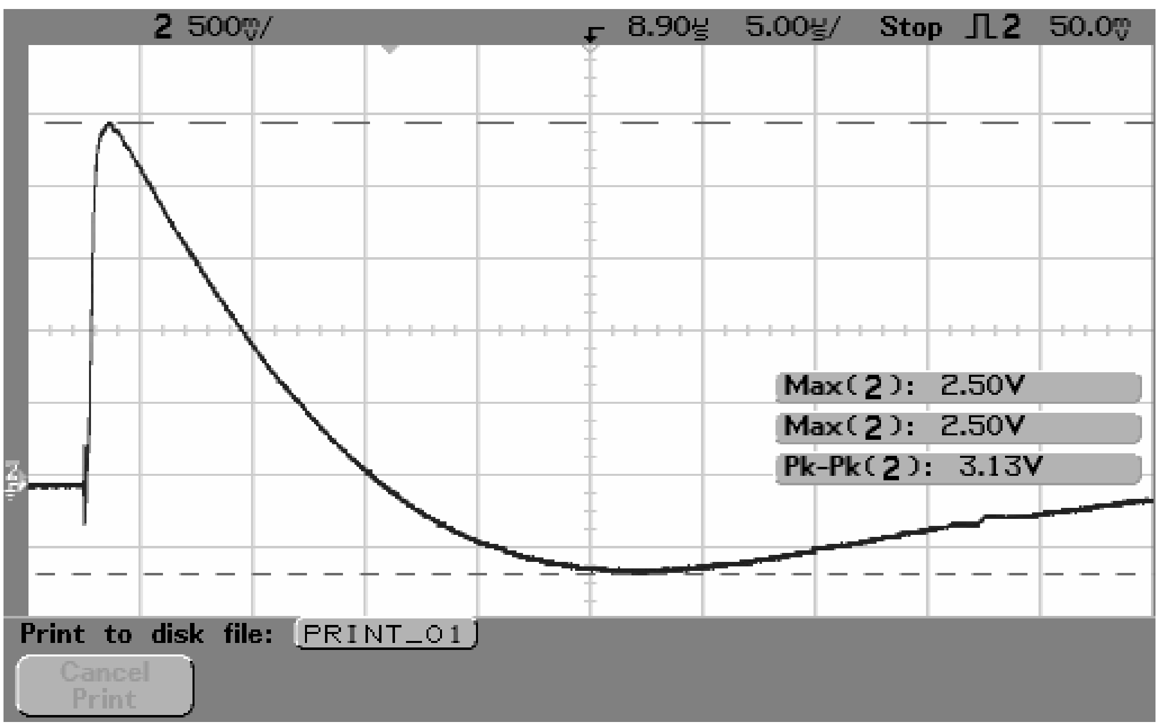


Figure A.1. V-CRO (input voltage) for EDCO FASTEL-FDOT Surge Suppressor

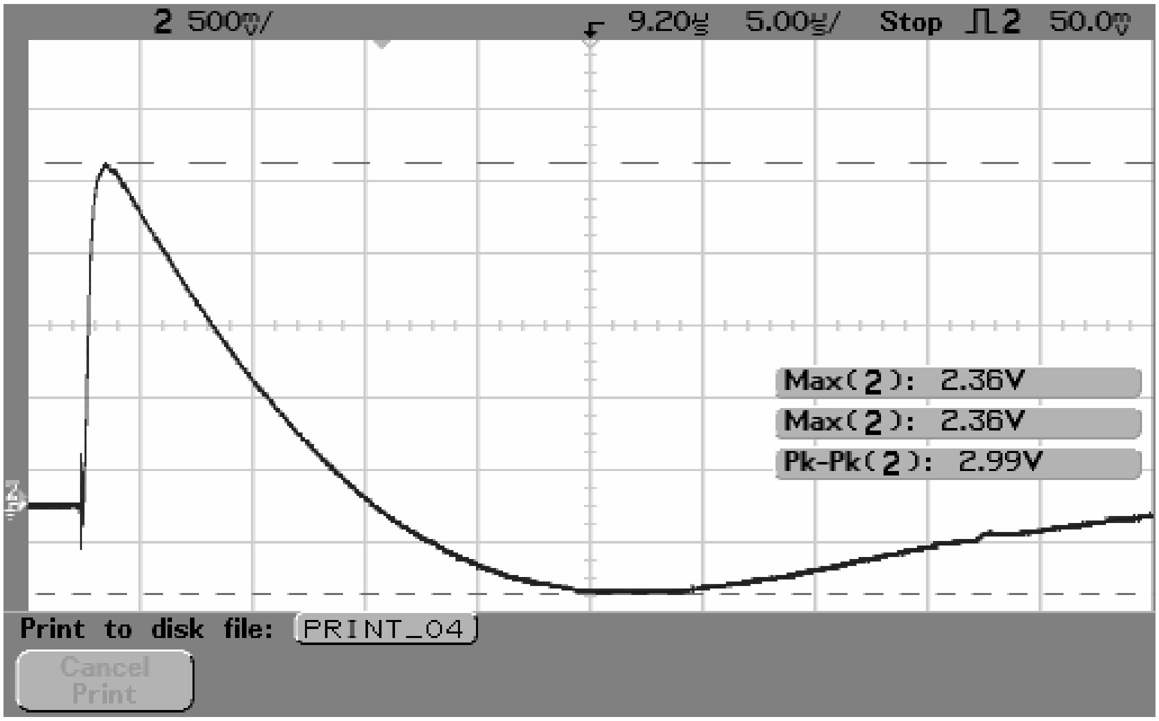


Figure A.2. V-CRO (input voltage) for CITEL BP1 T Surge Suppressor

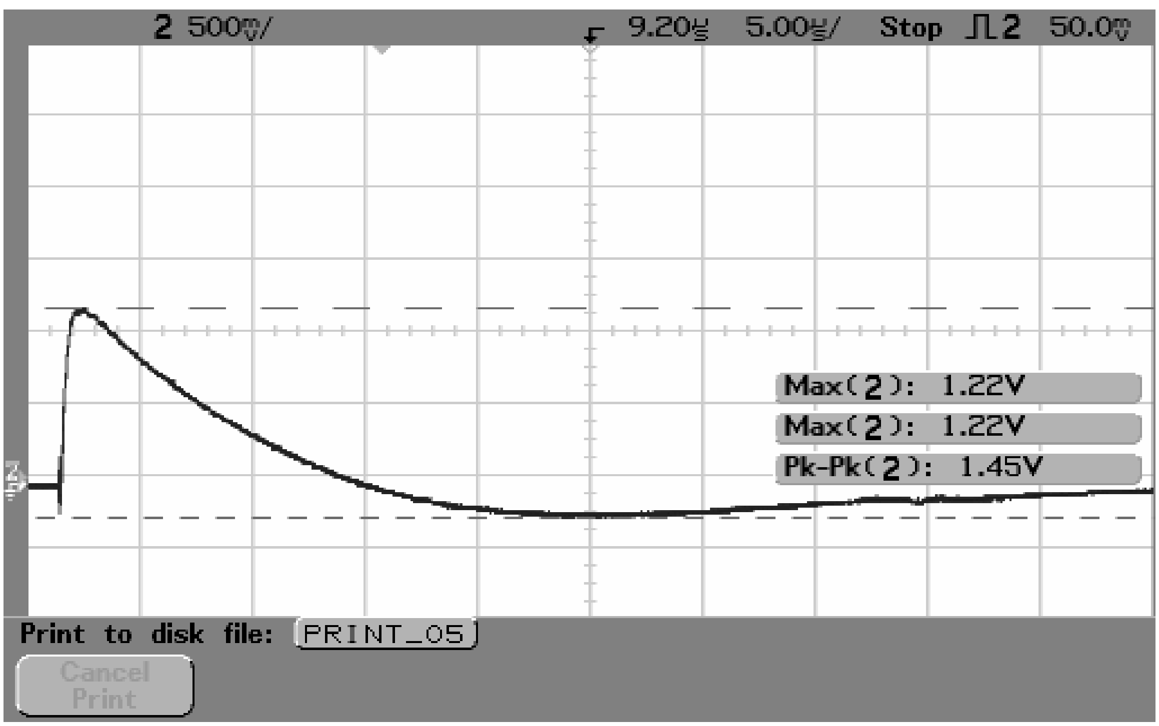


Figure A.3. V-CRO (input voltage) for CITEL B180MJ6 Surge Suppressor

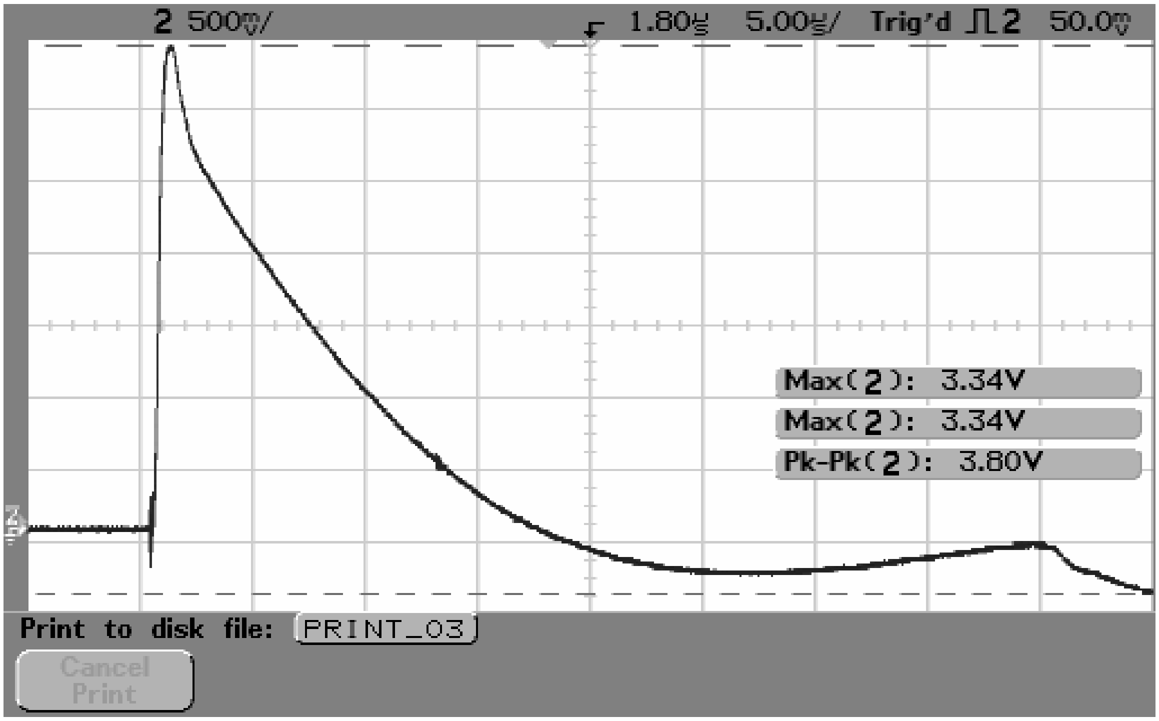


Figure A.4. V-CRO (input voltage) for S-TC-2 Surge Suppressor

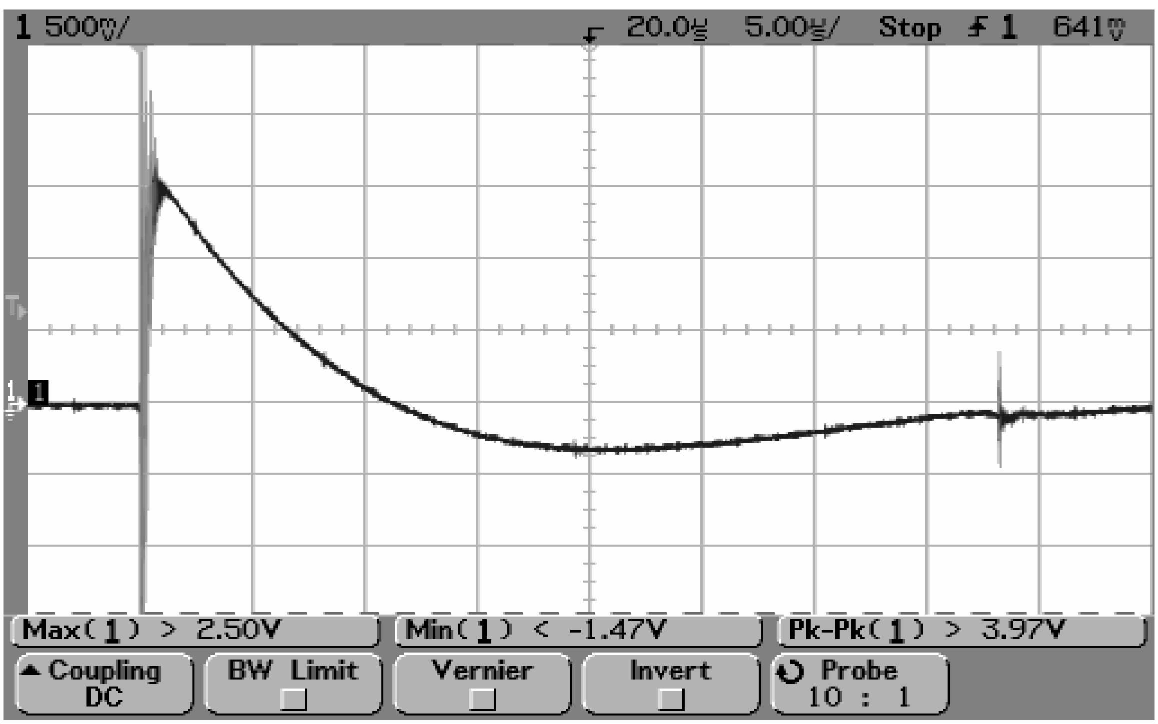


Figure A.5. V-CRO (input voltage) for S-D140-2X Surge Suppressor

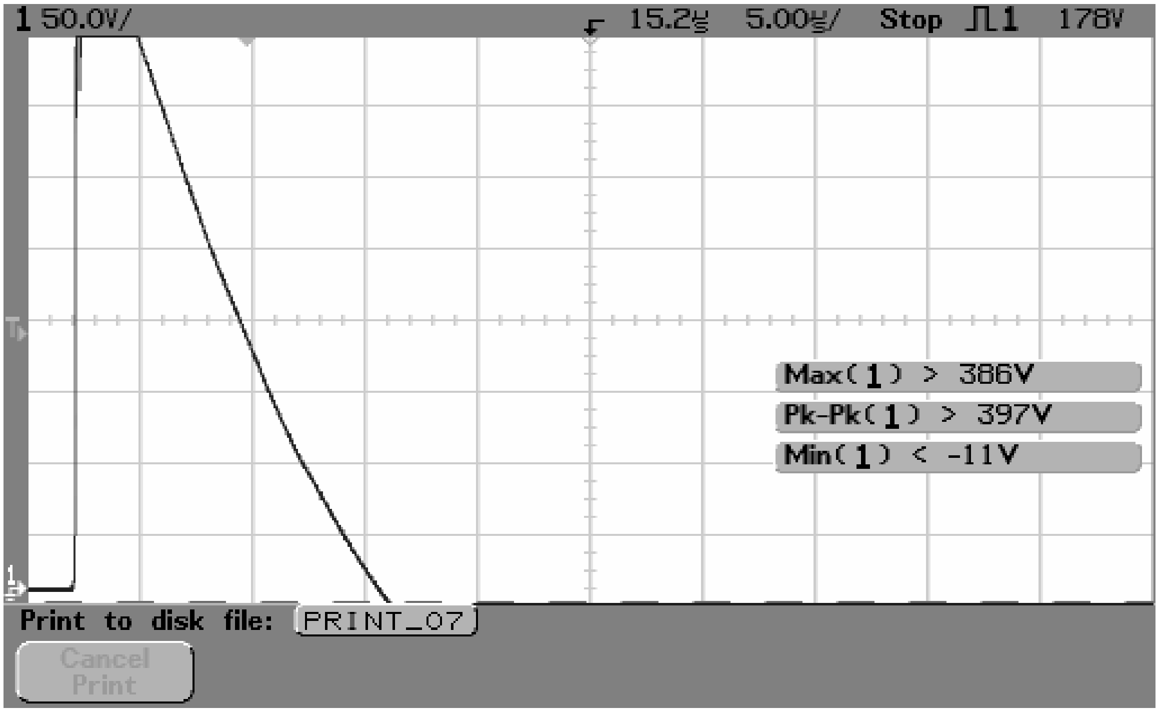


Figure A.6. EDCO FASTEL-FDOT Surge Suppressor Output Voltage

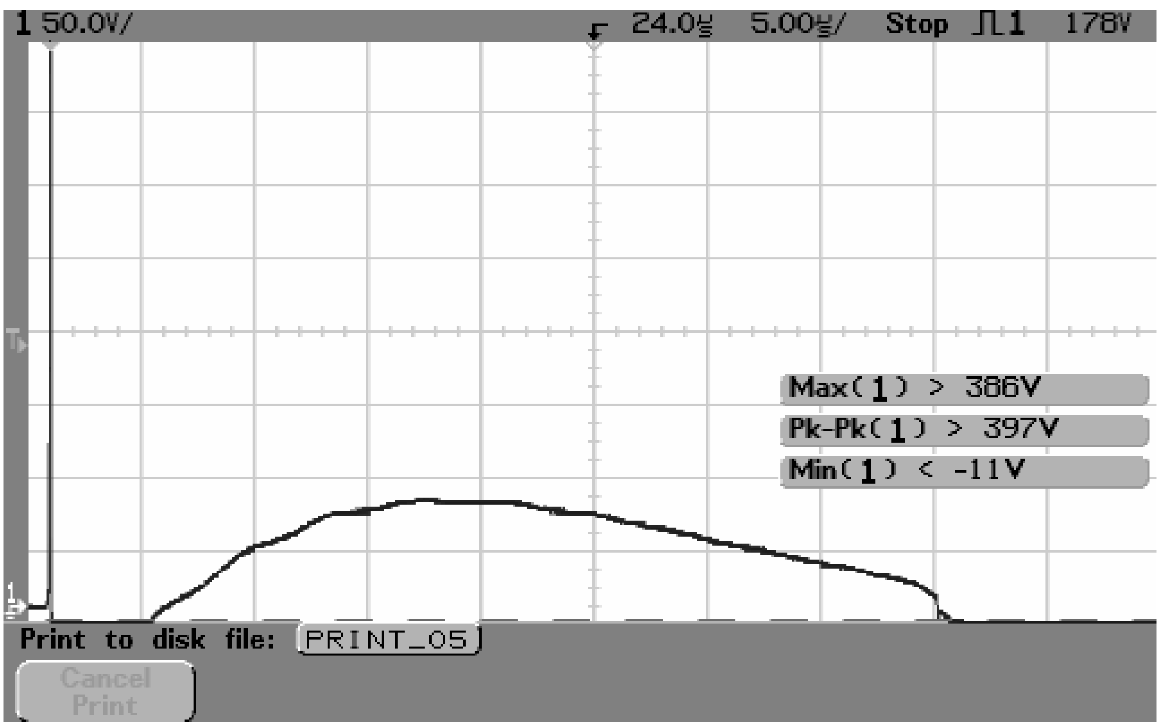


Figure A.7. CITEL BP1 T Surge Suppressor Output Voltage

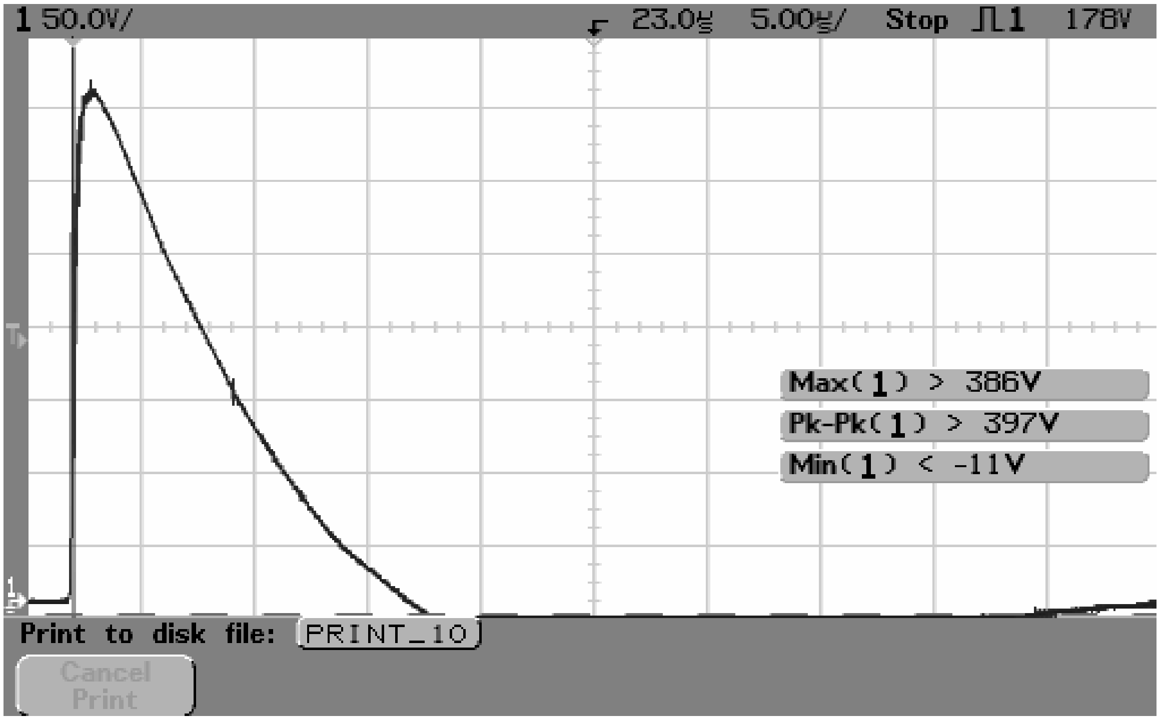


Figure A.8. CITEL B180MJ6 Surge Suppressor Output Voltage

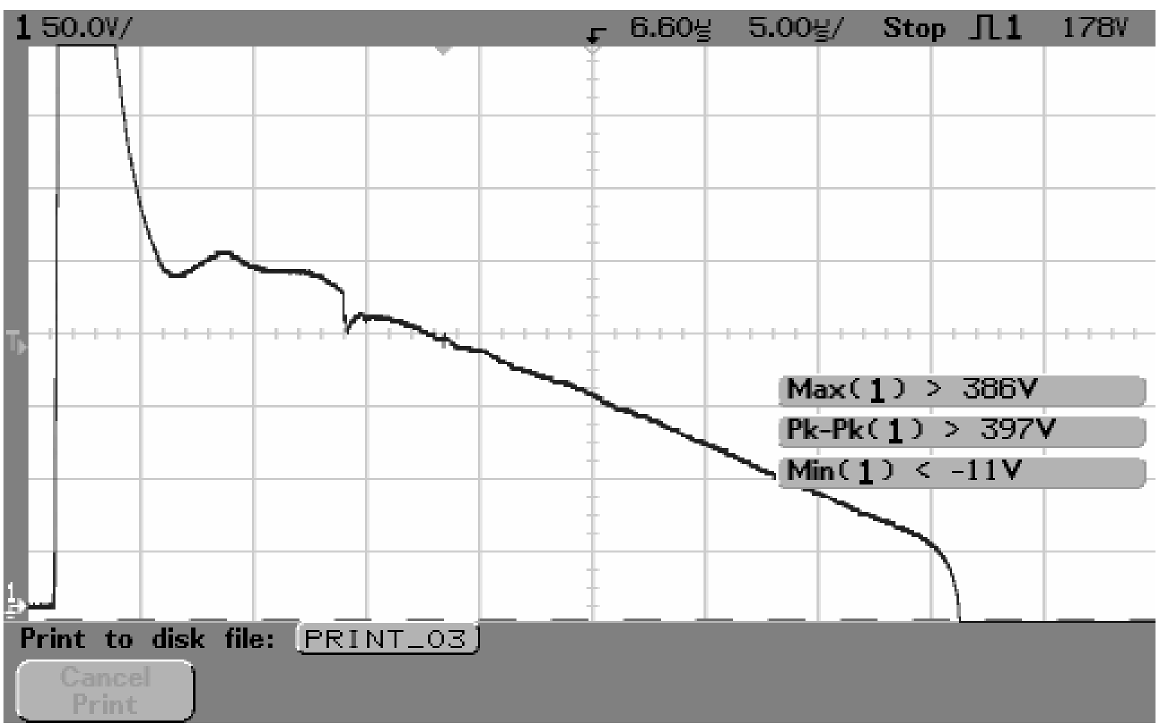


Figure A.9. S-TC-2 Surge Suppressor Output Voltage

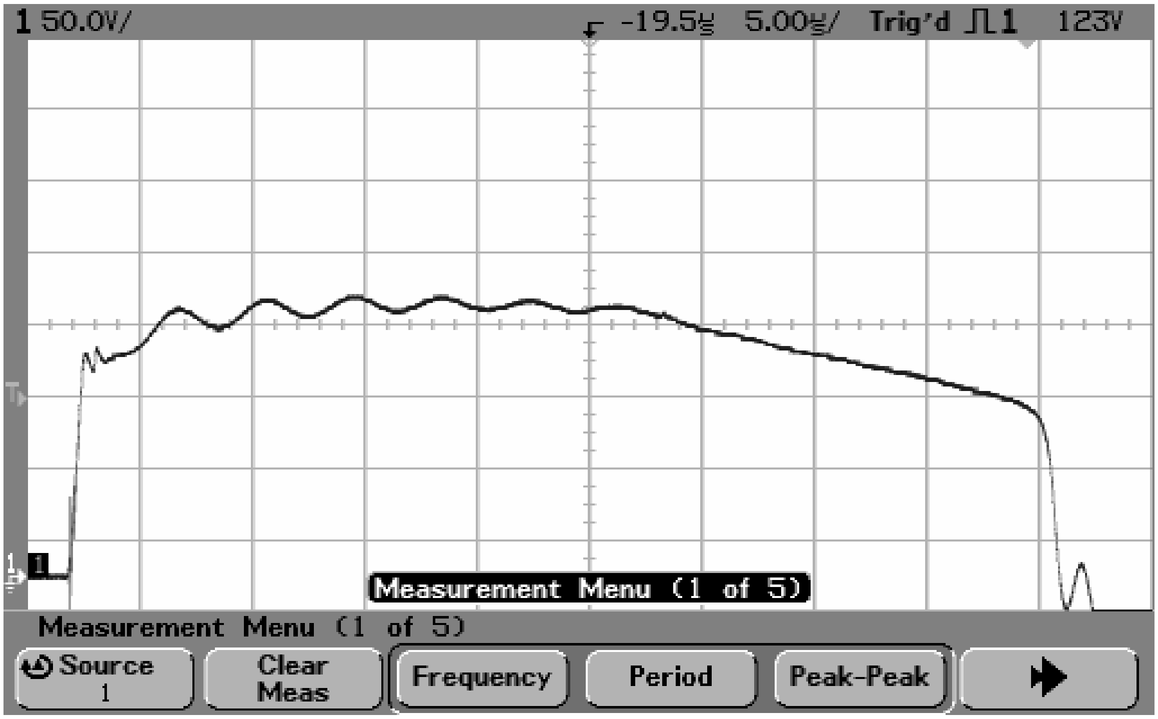


Figure A.10. Thomlinson Surge Suppressor Output Voltage

APPENDIX B - DAILY SURGE SUMMARY

Site 245: Lloyd (Hwy 59 N. of Hwy 90)				Site 192: Youngstown (Hwy 20 at Hwy 231)					Site 192: 9906 (I-4 Deltona)		
Date	Total # Surges	# Ringe Pulses		Date	Total # Surges	# Ringe Pulses			Date	Total # Surges	# Ringe Pulses
6/28/2001	1	0		6/28/2001					6/28/2001		
6/29/2001	9	8		6/29/2001					6/29/2001		
6/30/2001	2	0		6/30/2001					6/30/2001		
7/1/2001	0	0		7/1/2001					7/1/2001		
7/2/2001	0	0		7/2/2001	BEGAN TESTING 7/3/01				7/2/2001		
7/3/2001	0	0		7/3/2001	65	10			7/3/2001		
7/4/2001	0	0		7/4/2001	39	5			7/4/2001		
7/5/2001	0	0		7/5/2001	303	63			7/5/2001		
7/6/2001	0	0		7/6/2001	96	10			7/6/2001		
7/7/2001	0	0		7/7/2001	106	7			7/7/2001		
7/8/2001	0	0		7/8/2001	37	0			7/8/2001		
7/9/2001	0	0		7/9/2001	127	6			7/9/2001		
7/10/2001	0	0		7/10/2001	133	8			7/10/2001		
7/11/2001	0	0		7/11/2001	0	0			7/11/2001		
7/12/2001	0	0		7/12/2001	266	17			7/12/2001		
7/13/2001	0	0		7/13/2001	1	0			7/13/2001		
7/14/2001	0	0		7/14/2001	181	41			7/14/2001		
7/15/2001	0	0		7/15/2001	76	1			7/15/2001		
7/16/2001	0	0		7/16/2001	2	0			7/16/2001		
7/17/2001	0	0		7/17/2001	19	0			7/17/2001		
7/18/2001	0	0		7/18/2001	10	0			7/18/2001		
7/19/2001	0	0		7/19/2001	9	0			7/19/2001		
7/20/2001	2	0		7/20/2001	38	0			7/20/2001		
7/21/2001	7	1		7/21/2001	438	18			7/21/2001		
7/22/2001	5	0		7/22/2001	41	0			7/22/2001		
7/23/2001	0	0		7/23/2001	33	1			7/23/2001		
7/24/2001	0	0		7/24/2001	23	2			7/24/2001		
7/25/2001	0	0		7/25/2001	66	1			7/25/2001		
7/26/2001	0	0		7/26/2001	20	1			7/26/2001		
7/27/2001	0	0		7/27/2001	4	0			7/27/2001		
7/28/2001	0	0		7/28/2001	354	55			7/28/2001		
7/29/2001	0	0		7/29/2001	0	0			7/29/2001		
7/30/2001	0	0		7/30/2001	0	0			7/30/2001		
7/31/2001	0	0		7/31/2001	0	0			7/31/2001		
8/1/2001	0	0		8/1/2001	0	0			8/1/2001		
8/2/2001	0	0		8/2/2001	0	0			8/2/2001		
8/3/2001	0	0		8/3/2001	0	0			8/3/2001		
	ENDED TESTING AT THIS SITE			8/4/2001	0	0			8/4/2001	BEGAN TESTING 8/5/01	
TOTALS	26	9		8/5/2001	0	0	T.S. Barry		8/5/2001	0	0
Days	37	37		8/6/2001	0	0	T.S. Barry		8/6/2001	0	0
Ave/Day	0.70	0.24		8/7/2001	0	0	T.S. Barry		8/7/2001		
				8/8/2001	0	0			8/8/2001		
				8/9/2001	0	0			8/9/2001		
				8/10/2001	5	1			8/10/2001		
				8/11/2001	59	15			8/11/2001		
				8/12/2001	1	0			8/12/2001		
				8/13/2001	64	12			8/13/2001		
				8/14/2001	11	1			8/14/2001		
				8/15/2001	177	1			8/15/2001		
				8/16/2001	461	70			8/16/2001		
				8/17/2001	3	0			8/17/2001		
				8/18/2001	7	0			8/18/2001		
				8/19/2001	248	11			8/19/2001		
				8/20/2001	191	16			8/20/2001		
				8/21/2001	17	0			8/21/2001		
				8/22/2001	0	0			8/22/2001		
				8/23/2001	0	0			8/23/2001		
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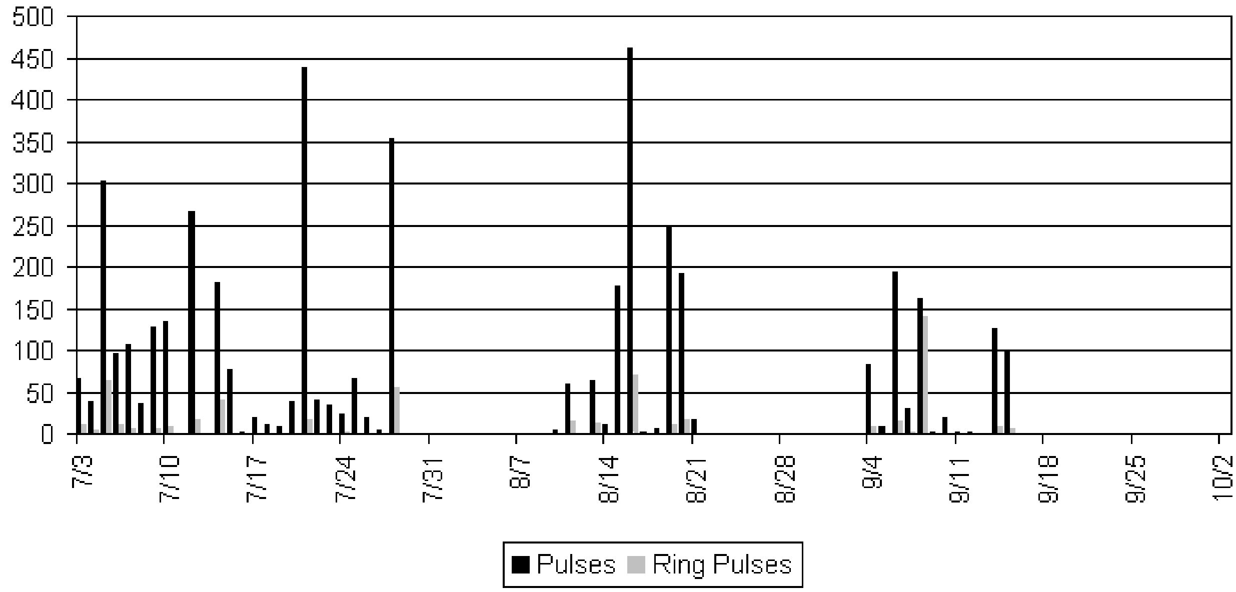
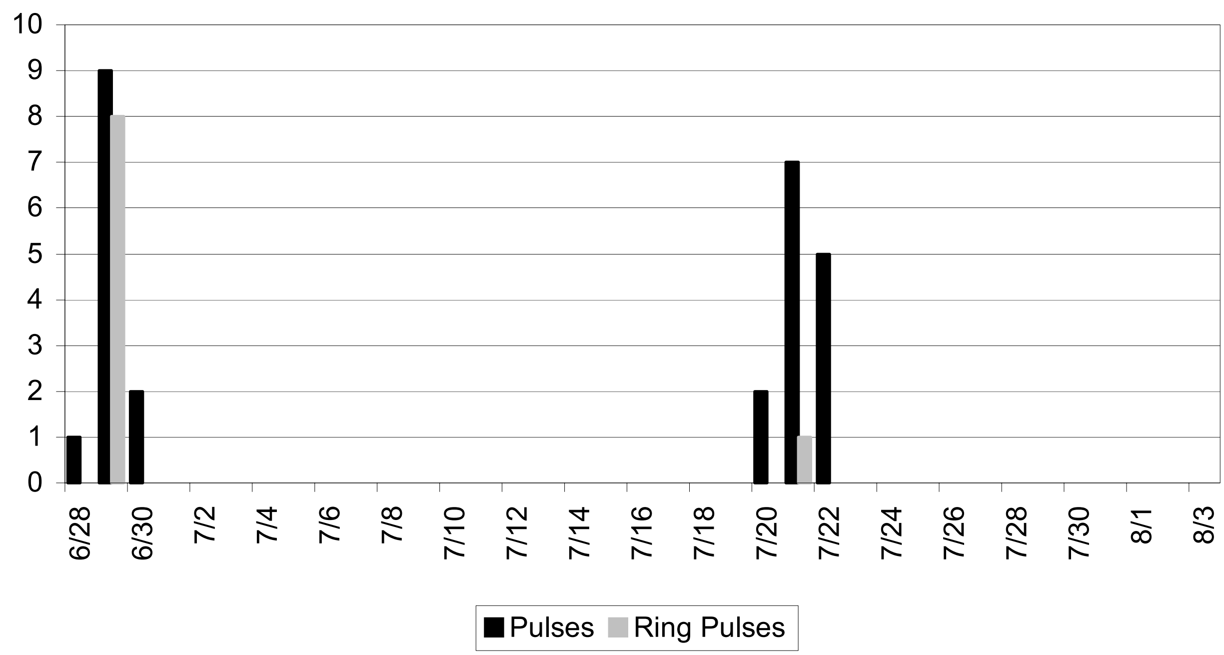
				8/26/2001	0	0			8/26/2001		
				8/27/2001	0	0			8/27/2001		
				8/28/2001	0	0			8/28/2001		
				8/29/2001	0	0			8/29/2001		
				8/30/2001	0	0			8/30/2001		
				8/31/2001	0	0			8/31/2001		
				9/1/2001	0	0			9/1/2001		
				9/2/2001	0	0			9/2/2001		
				9/3/2001	0	0			9/3/2001	90	3
				9/4/2001	83	9			9/4/2001	0	0
				9/5/2001	9	0			9/5/2001		
				9/6/2001	193	15			9/6/2001		

Site 192 Daily Lightening Surge Counts 2001



Site 245 Daily Lightening Surge Counts 2001



APPENDIX C – SURGE SUPPRESSOR DATA SHEETS

C.1 Surge Suppression, Inc. Data Sheets

Transient Voltage Surge Suppressors By:

Surge Suppression® Incorporated

Manufacturer and Supplier of Quality TVSS Systems

Telephone Line Models

Network Data Circuit protection device with Discrete All-Mode Protection

Made in the USA

"Our Name Says It All"

P.O. Box 674
Destin, FL 32540-0674
Phone: 888-987-8877
Fax: 888-900-8879
www.surgesuppression.com

The Telephone Line devices are designed to protect standard voice grade telephone lines. These devices are intended for installation at the telephone demarcation point so as to allow for a common grounding point.

This device is available for a variety of line connections (1, 2, 3 or 6 pair) accomplished by using terminal strips or (1 or 2 pair) using standard RJ-11 or RJ-14 connectors, making your installation a breeze. A ground lug is provided on the face of the unit to insure a low impedance ground discharge path.

The unique design of these devices make them among the most versatile TVSS devices on the market with performance specs that are superior to our competitors and a warranty that is second to none.

GENERAL	
Description:	Series wired transient voltage surge suppressor with encapsulated Optimal Response Network™ circuitry for protection of voice grade telephone circuits.
Application:	Standard 3002/C2 unconditioned voice grade lines, fax lines, modem lines and **ISDN** lines to protect data transmission system equipment from damaging transients generated outside of the facility.
Warranty:	**25 Years Unlimited Free Replacement**

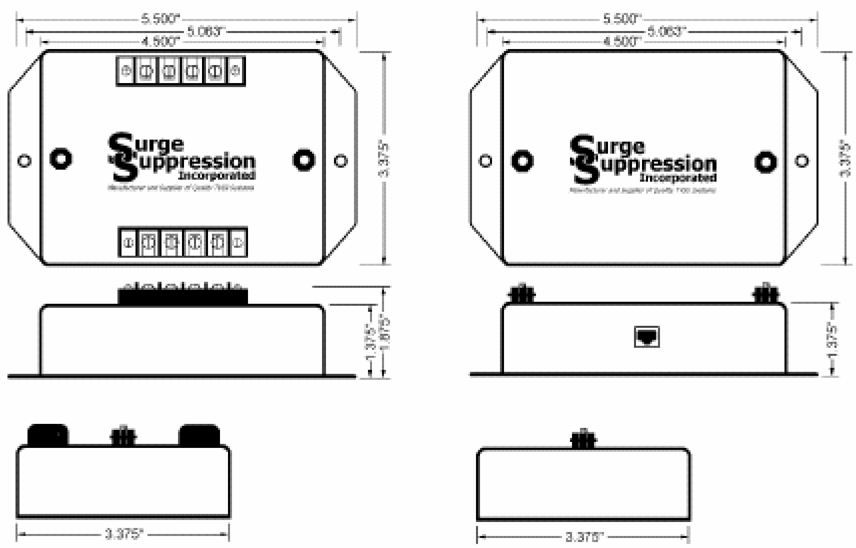
MECHANICAL	
Enclosure:	Plastic, UL 94V
Physical Dimensions:	5.5" X 3.375" X 1.875" (1,2,3 pair terminal, RJ11, RJ14) 7.3" X 4.7" X 2.8" (6 pair terminal)
Mounting:	External mounting feet.
Connection Method:	Standard screw terminals (TC models) or RJ-11 or RJ-14 modular connectors (RJ models)
Shipping Weight:	• 1lbs

CIRCUITRY	
Circuit Design:	Series wired, parallel connected hybrid design incorporating discrete all mode protection and utilizing our encapsulated Optimal Response Network™ design to provide lowest possible let-through-voltages. All suppression circuits are completely encapsulated in our exclusive compound to assure long component life and complete protection from the environment and/or vibration.
Protection Modes:	Discrete All Mode – Tip to Ring (Normal Mode); Tip to Ground and Ring to Ground (Common Mode)
Maximum Data Rate:	Up to 100kbits/sec

PERFORMANCE	
Maximum Continuous Operating Voltage:	130Vrms
Maximum Continuous Operating Current:	360ma
Peak Surge Current per Pair:	30,000 amps per pair
Response Time:	<1 nanosecond

Models Available	
S-TC-2	Single Pair – Terminal Connected
S-TC-4	Two Pair – Terminal Connected
S-TC-6	Three Pair – Terminal Connected
S-TC-12	Six Pair – Terminal Connected
S-RJ-11	One Pair – RJ-11 Modular Connection
S-RJ-14	One or Two Pair – RJ-14 Modular Connection

<table>
<tr><td colspan="2">ANSI/IEEE C62.41-1991
Let-through Voltage Tests</td><td rowspan="3">Let-through Voltage test Environment using ANSI/IEEE C62.41-1991, C62.45-1992; Static, Positive Polarity All voltages are peak (±10%), Time base = 1ms</td></tr>
<tr><td>Test Mode</td><td>Test Category B3/C1 Impulse Wave 6,000V 3,000A</td></tr>
<tr><td>L-L
L-G</td><td>350
350</td></tr>
</table>



Terminal Strip Connection **Modular RJ-14 Connection**

S-TC-12 model dimensions are 7.3" X 4.7" X 2.8"

Transient Voltage
Surge Suppressors By:

S-Dxx-xX
Data Line Models

Network Data Circuit protection device with Discrete All-Mode Protection

Surge Suppression® Incorporated
Manufacturer and Supplier of Quality TVSS Systems

Made in the USA

"Our Name Says It All"

P.O. Box 674
Destin, FL 32540-0674
Phone: 888-987-8877
Fax: 888-900-8879
www.surgesuppression.com

The Series S-Dxx-xX devices are designed to protect data transmission circuits. These devices are intended for installation near the equipment to be protected and mounted as close to the electrical power source of the equipment as possible so as to allow for a common grounding point for grounding.

This device is available for two to twelve wire data line connections (1 to 6 pair) accomplished by using the terminal strips provided, making your installation a breeze. Two ground lugs are provided on the face of the unit to insure a low impedance ground discharge path.

The unique design of these devices make them among the most versatile TVSS devices on the market with performance specs that are superior to our competitors and a warranty that is second to none.

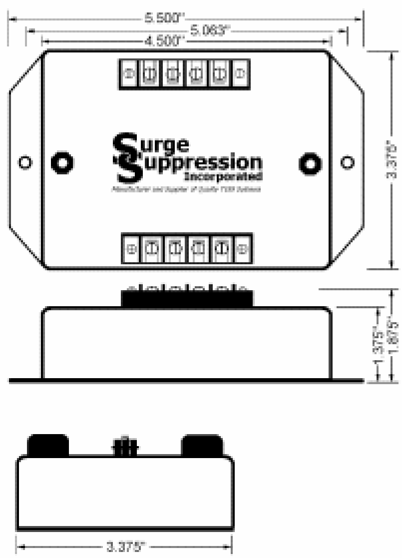
GENERAL	
Description:	Series wired transient voltage surge suppressor with encapsulated **Optimal Response** Network™ circuitry for protection of data circuits.
Application:	Designed for use data, signal and current loop circuits to protect data transmission system equipment from damaging transients generated between terminals and equipment in the data collection/transmission system.
Warranty:	**25 Years Unlimited Free Replacement**

MECHANICAL	
Enclosure:	Plastic, UL 94V
Mounting:	External mounting feet.
Connection Method:	Wire clamping box terminals located at the input and output sides of the device. Wire size: Lines #18-22 AWG, Ground #6-12 AWG.
Shipping Weight:	• 1lbs

CIRCUITRY	
Circuit Design:	Series wired hybrid design incorporating discrete all mode protection and utilizing our encapsulated **Optimal Response** Network™ design to provide lowest possible let-through voltages. All suppression circuits are completely encapsulated in our exclusive compound to assure long component life and complete protection from the environment and/or vibration.
Protection Modes:	Dedicated protection components and circuitry for each mode. Discrete L-L (Normal Mode) and L-G, Shield-G (Common Mode)
Maximum Data Rate:	10.0 Mbps

PERFORMANCE	
Maximum Continuous Operating Voltage:	7.5VDC, 15VDC, 36VDC, 54VDC and 1400VDC
Maximum Continuous Operating Current:	360ma
Maximum Data Rate:	10.0 Mbps
Peak Surge Current per Pair:	L-L 10kA, L-G 10kA
Response Time:	<1 nanosecond

Let-Through Voltages Using ANSI/IEEE C62-41-1991 Test Environment: Static, positive polarity. All voltages are peak (±10%). Time base=5μsec.				
Model	Maximum Continuous Operating Voltages	Maximum Continuous Operating Current	Test Mode	B3/C1 Impulse Wave 6,000V, 3000A
S-D5-2X S-D5-4X S-D5-6X S-D5-8X S-D5-12X	7.5VDC L-G 7.5VDC L-L 70 Shield-G	360mA	L-G L-L Shield-G	<20 <30 <170
S-D15-2X S-D15-4X S-D15-6X S-D15-8X S-D15-12X	15VDC L-G 15VDC L-L 70 Shield-G	360mA	L-G L-L Shield-G	<30 <40 <170
S-D33-2X S-D33-4X S-D33-6X S-D33-8X S-D33-12X	36VDC L-G 36VDC L-L 70 Shield-G	360mA	L-G L-L Shield-G	<70 <70 <170
S-D53-2X S-D53-4X S-D53-6X S-D53-8X S-D53-12X	54VDC L-G 54VDC L-L 70 Shield-G	360mA	L-G L-L Shield-G	<80 <90 <170
S-D140-2X S-D140-4X S-D140-6X S-D140-8X S-D140-12X	140VDC L-G 140VDC L-L 70 Shield-G	360mA	L-G L-L Shield-G	<180 <180 <170

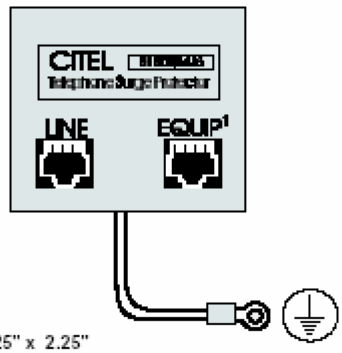


Data Line Models

Image is S-Dxx-4X Model

C.2 Citel Data Sheets

Surge Protector for One and Two Pair Telephone Lines B180T/MJ6 and B280T/MJ6



Dimensions: (H-W-D) 0.75" x 1.25" x 2.25"

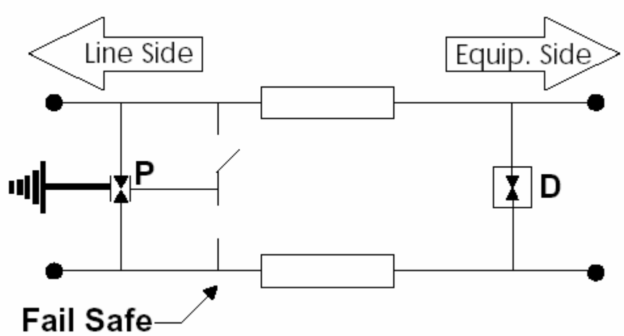
The Citel B180T/MJ6 and B280T/MJ6 have been designed to protect modems, fax machines, key systems, alarm systems, dialers, and payphones against lightning surges and electrical transients. This module uses a state-of-the-art multistage circuitry and will automatically reset after every electrical strike. I/O connections are via RJ11 jacks and a 10 ft. long RJ11 cable is provided.

- **Ultra fast response time - less than 1 ns**
- **Multi-stage circuitry**
- **Comes with a velcro for easy mounting**
- **Available for one and two pair lines**

Electrical Specifications B180T/MJ6 and B280T/MJ6

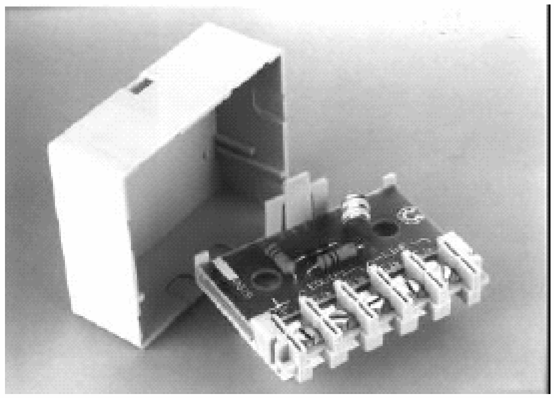
	B180T/MJ6	B280T/MJ6
Application:	Telephone Lines	Telephone Lines
Series Resistance:	4.7 ohms	4.7 ohms
Capacitance:	< 70 pF	< 70 pF
Maximum Line Current:	200mA	200mA
Maximum Line Voltage:	170 V	170 V
Clamping Voltage:	190 V	190 V
Rated Energy Dissipation:	200 J	200 J
Power Handling: (8/20µs- 10 x's)	10 kA	10 kA
End of Life Characteristics: (U=220Veff/Icc>10A)	Short Circuit	Short Circuit
Pins Protected:	3, 4	2, 3, 4, 5

Electrical Diagram



P: 3-element gas tube
D: Solid state diode

Surge Protector for Telephone and Data Lines BP1



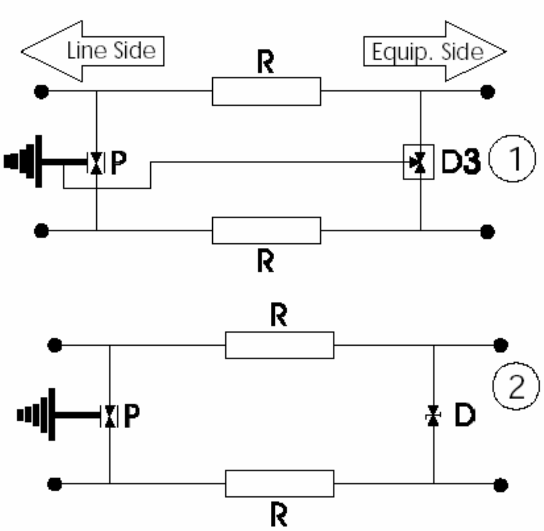
The BP1 surge protectors have been designed to protect small PABX's, key systems, modems, data circuits, and more specifically RS232,RS422, RS423, RS 485 and 4 - 20 mA loops against lightning surges and electrical transients. In the case of unusual surges, the unit will fail short leaving your equipment fully protected.

- **Ultra fast response time**
- **Multiple stage circuitry**
- **Protects One Pair (Two Wires)**
- **Can be easily mounted on a wall or backboard**

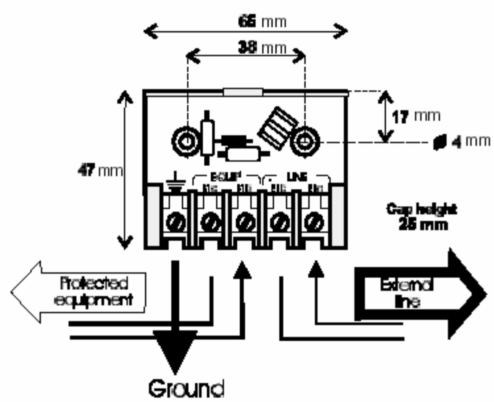
Electrical Specifications BP1

	BP1 - T	BP1 - 48V	BP1 - 24V	BP1 - 12V	BP1 - 6V
Application:	Telephone Lines	Leased Lines	4-20 mA loop Lines	Telemetry	RS485
Series Resistance:	4.7 Ω	4.7 Ω	4.7 Ω	4.7 Ω	4.7 Ω
Capacitance:	70 pF	200 pF	300 pF	400 pF	900 pF
Maximum Line Current:	200 mA	200 mA	200 mA	200 mA	200 mA
Maximum Line Voltage:	170 V	48 V	24 V	15 V	6 V
Clamping Voltage:	190 V	60 V	30 V	20 V	10 V
Residual Voltage:	220 V	70 V	35 V	30 V	20 V
Power Handling: (8/20µs- 10 x's)	10 kA	10 kA	10 kA	10 kA	10 kA
End of Life Characteristics: (U=220Veff/Icc>10A)	Short Circuit	Short Circuit	Short Circuit	Short Circuit	Short Circuit
Electrical Diagrams:	2	1	1	1	1

Electrical Diagrams



Mechanical Diagram



P: 3- Element Gas Tube
R: Resistor
D: Clamping Diode
D3: 3 - Element Clamping Diode

C.3 EDCO Data Sheets

EDCO Transient Voltage Surge Suppression

Telecom/Datacom Products

FAS-TEL and FAS-31XT

RJ11/RJ31X Telephone Protection

The **FAS-TEL** and **FAS-31XT** are single-pair telephone or data line protectors that implement advanced two-stage hybrid design. These units address overvoltage transients with silicon breakover devices, while sneak and fault currents are mitigated with PTC technology which consists of solid-state resettable fuses.

FAS-31XT replaces the RJ31X jack with a protected version. Four screw terminals are provided to wire the protector in the same manner as a standard RJ31X jack. The **FAS-31XT** can be used alone or as an accessory to the TS-500G or TS-500F AC Power Surge Protector. The TS-500G and TS-500F provide a convenient grounding point for the **FAS-31XT/FAS-TEL** ground wire.

The **FAS-TEL** is nearly identical to the **FAS-31XT** except without the shorting bars. Two screw terminals are provided to connect Telco Line to protector. Protected equipment such as modems are plugged into female modular jack on the **FAS-TEL**.

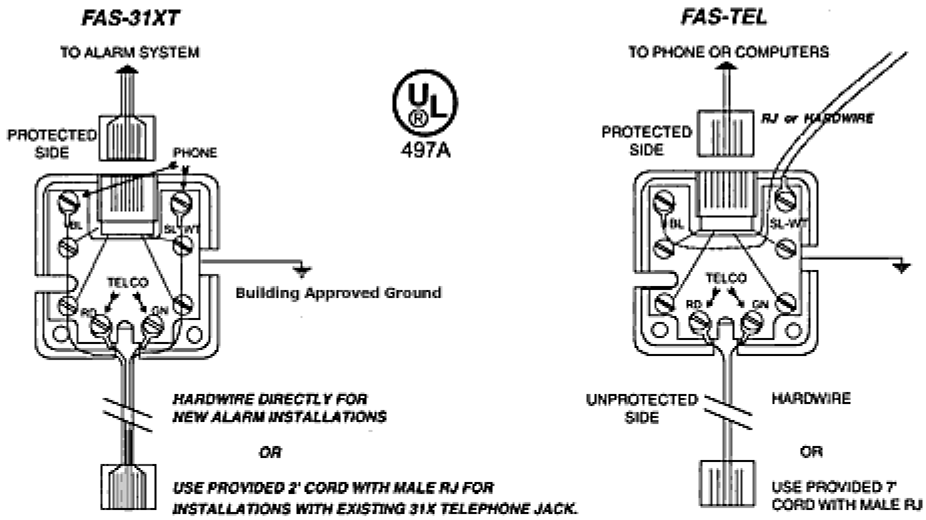
FEATURES
• ‹1 Nanosecond Response Time
• Solid-State Silicon Breakover Technology
• Low Capacitance
• Overcurrent Protection
• UL 497A Listed
• Line-to-Line Protection
• Line-to-Ground Protection
• Polyswitch Resettable Fuses—PTCs

497A

SPECIFICATIONS							
Part #	Max Peak Signal Voltage	Nominal Breakdown Voltage	Max Current Ip 10 x 1000µs	Max Clamp Volt. @Ip	Typ Cap (pf)	Max Continuous Current	Nominal Series Resistance
FAS-TEL-015T	12	15	124	20	2100	150mA	8 Ohms
FAS-TEL-030T	24	30	71	38	1180	150mA	8 Ohms
FAS-TEL-050T	43	50	45	57	900	150mA	8 Ohms
FAS-TEL-060T	52	60	36	66	750	150mA	8 Ohms
FAS-TEL-200T	220	270	100A (T-G) + (R-G)	10*	50	150mA	8 Ohms
FAS-31XT	220	270	100A (T-G) + (R-G)	10*	50	150mA	8 Ohms
FAS-TEL-DSL	285	300	100A (T-G) + (R-G)	10*	50	150mA	8 Ohms

* NOTE: Forward Voltage After Breakover

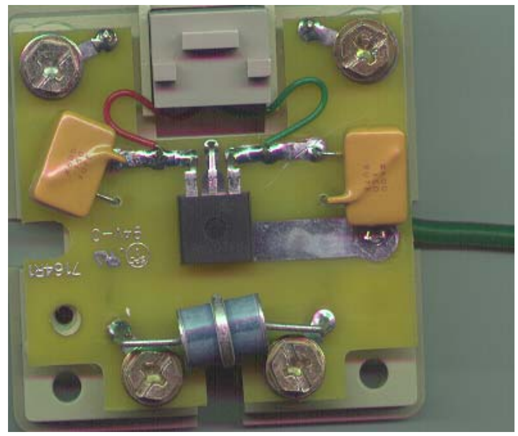
INSTALLATION



APPENDIX D – SURGE SUPPRESSOR TEST SETUP AND PROCEDURES

These tests were designed to run using the MIG surge generator shown below. The following steps are taken to test a surge suppressor:

Current Generator



Surge Suppressor

D.1 Surge Suppressor Test Procedure

1. Plug the current generator into the wall outlet.
2. Flip the black power switch in the back on (position I).
3. In the front, push the *ON/STBY* button. With the equipment on, the lid can now be opened. Therefore, open the lid.
4. Connect the surge suppressor input (line side, not the modem side) to the red terminal of the surge generator.
    a. If the surge suppressor has screw terminals as shown above, connect one of the terminals on the suppressor to the red terminal on the surge generator using 10 – 14 gauge wire.
    b. If the suppressor has a telephone modular jack input (as shown for the modem output of the suppressor above), a modified telephone extension wire (modem cord) must used. Cut an extension cord to a length of about 10 inches and strip approximately ½ inch of the red or green wire. Plug the jack into the suppressor input (line) side and connect either the red or green (not both) to the red terminal on the surge generator

5. Connect the ground wire of the suppressor to the black knob of the surge generator.

   Note: For any surge suppressor, connect one input to the red button and the ground wire to the black button.

6. Place the surge suppressor onto the generator, close the lid on the surge generator and press the *MAIN* (soft key *F6*) button below the LCD display on the front panel.

7. Push the down arrow button until the current reading (*IPEAK*) is selected. Press the *EDIT* button and enter the desired surge current in Amps. This current can be anywhere from 250 to 6100 Amps. *For acceptance tests of telephone line surge suppressor, 6000 Amps is recommended*.

8. Press the enter (↵) button.

9. Press the down arrow button until the *NUM of PULSES* box is selected. Press *EDIT*, enter the number of surge pulses desired for the test and press the enter button. *For acceptance tests of telephone line surge suppressors, 10,000 pulses are recommended.*

10. Press the down arrow button until the *REPETITION* box is selected. Press *EDIT*, enter the desired number seconds (interval) between pulses (surges) and press the enter button. The minimum pulse interval is determined by the current (*IPEAK*) selected. If pulse interval entered is less than the required minimum time interval, a warning will be issued and the surge generator will set the minimum time automatically.

11. Close the lid and press the *RUN* button (red button). The number and intensity of surges selected will be applied to the surge suppressor.

Note: To observe the input waveforms on an oscilloscope, the following steps should be observed.

a. The front of the current generator panel has three BNC outputs that can be used to see the waveforms. The top two are for voltage (V-CRO) and current (I-CRO). Plug one end of the BNC cable into the current generator and the other end into the oscilloscope.

b. Change the time per division and voltage per division scales until one has the required scales to capture the waveform. Remember since this current generator simulates a lightning impulse, it has an 8/20 μSec pulse. This means 8 μsec to rise to its peak and 20 μsec for half of it to have gone. So, one will need at least a time division of 5 μSec depending on the number of squares available.

c. Once the required waveform has been captured, it should be noted the signal scale is one Volt for every 600Volts for V-CRO and one Volt for every 600 Amps for I-CRO.

D.2 Suppressor Verification Test Procedure

These are the guidelines to follow to test the surge suppressor to see it if it still functioning after the test surges have been applied to the suppressor.

Note: If the suppressor has disintegrated or blown up, skip this part.

1. Verify the surge generator has completed the programmed surges. If not, stop it by pressing RUN button.
2. Open cover of current generator and remove suppressor.
3. Take suppressor and wire it up according to Figure 5A or 5B
4. Pick up the telephone receiver and listen for a dial tone. Dial a telephone number to verify a call can be made.
   a. Do you hear a dial tone when you pick up the phone? Yes No
   b. Can you make a call with suppressor as part of the circuit? Yes No

If the answers to all the questions are "Yes", repeat the tests and administer another round of surges on the surge suppressors and once you are done, repeat the above questions. If questions 5 and 6 are No, then the surge suppressor has been damaged or destroyed.

Appendix D
Evaluation of Bonding Materials Used in Piezoelectric Axle Sensor Installation Task Report

Included in this appendix is the task report on the study of bonding materials for piezoelectric axle sensors.

EVALUATION OF BONDING MATERIALS USED IN PIEZOELECTRIC AXLE SENSOR INSTALLATION

Conducted by:

RENATUS MUSSA, Ph.D., P.E.
Assistant Professor
and
THOBIAS SANDO
Graduate Research Assistant

Department of Civil Engineering
FAMU-FSU College of Engineering
Tallahassee, Florida
Tel: 850-410-6191
Fax: 850-410-6142
Email: mussa@eng.fsu.edu

For:

Florida Department of Transportation
Transportation Statistics Office

DRAFT FINAL REPORT

September 2003

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EXECUTIVE SUMMARY

Introduction

The main goal of this research project was to develop test procedures that can be used to test adhesives for installation of piezoelectric axle sensors in the State of Florida. In addition, this research undertaking was also aimed at developing material specifications that will be used to select adhesives to achieve long-term field performance of piezoelectric axle sensors. The study was prompted by the fact that there are no standard procedures locally and nationally for testing adhesives and no state has so far developed material specifications for adhesives specifically for use in piezoelectric sensor installation.

Long-term observation of sensor performance in Florida suggested that the use of adhesives with characteristics unsuitable for Florida traffic, pavement, and environmental conditions might be contributing to premature failures of piezoelectric sensors. The excessive failures of piezos at telemetered traffic monitoring sites (TTMS) is of major concern to the Florida Department of Transportation (FDOT) because of the high cost of replacements and the attendant disruption of traffic flow. This executive summary gives an overview of adhesives approved for use in Florida, the methodology used in the study, findings, and recommendations.

Characteristics of adhesives approved by FDOT Planning Office

Information supplied by the Project Manager, Mulder Brown, indicated that there are five adhesives that have been approved for use in the State of Florida. These adhesives are G100 by E-Bond Epoxies, 7084 by Dynatron/Bondo Corporation, P5G by Electric Control Measurements, AS475 by International Road Dynamics Inc., and PU200 by Global Resins Limited.

G100 by E-Bond Epoxies: G100 is an epoxy-based material that has invariably been used in Florida for approximately 18 years for piezo installation and other purposes such as patching and placement of anchor bolts, dowels and pins in concrete surfaces. It is usually supplied in two parts, a resin and a hardener, in 11½, 26, and 46-pound containers. The resin and the hardener are mixed in 25 to 1 ratio by weight. The manufacturer technical data sheet indicates that the resin and hardener should be mixed within three to five minutes of opening the containers and poured immediately after mixing. The manufacturer recommends curing time of one hour to 14 hours depending on the substrate temperature. Lower substrate temperature requires longer curing period while higher substrate temperature requires shorter curing time, thus allowing faster opening of the road to traffic. It should be noted that originally G100 was formulated for installation of heavy WIM frames in portland cement concrete pavements in Texas.

7084 by Dynatron/Bondo Corporation: This is also an epoxy-based adhesive that is supplied in two parts—resin and hardener. Both the resin and a hardener are supplied in 12.6 pounds. The material is mixed in 1:1 ratio. The mixing time is not indicated in the technical data sheet. The data sheet does not indicate the mix cure time but indicates the gel time at 77^{o}F to be between 17 to 25 minutes.

ECM P5G by Electronic Control Measurement: This is an acrylic-based adhesive supplied in two parts—resin and hardener. The hardener is peroxide. ECM P5G is also mixed with fine filler material intended to improve bonding. The filler material commonly used is dry sand. The adhesive is supplied in 13.5 pounds containers. The manufacturer recommends that the resin should be premixed (without hardener) for four minutes or until the resin has a smooth/even texture. The hardener is then added and mixed for not more than one minute after which the binder is immediately used. The data sheet indicates that the expected cure times range from 20 minutes for 75^{o}F to 100^{o}F temperatures to 40 minutes for 40^{o}F to 50^{o}F temperatures.

AS475 by International Road Dynamics (IRD) Inc.: This adhesive is also acrylic-based and supplied in two parts—resin and hardener. The hardener is composed of benzyl peroxide organic (PBO) powder. The resin is supplied already pre-mixed with fine filler material that, according to the manufacturer, provides strength and consistency to the adhesive mixture. The filler material is made of fine aggregate and prevents the resin from cracking by serving as a heat sink for the significant heat created during the curing of the resin. The material is supplied in 39.6-pound pail for 12-foot sensors and 22-pound pails for 6-foot sensors. The manufacturer recommends thorough mixing of resin and filler material prior to adding the hardener. The hardener is added in an amount that is dependent upon the ambient temperature and mixed with resin and filler for approximately two minutes. The manufacturers indicate that the mixture cures fully in 30 to 40 minutes.

PU200 by Global Resins Limited: This is a polyurethane-based adhesive that is also supplied in two parts consisting of resin and hardener. In addition, the adhesive is supplied in two versions—one for winter installation when outside temperature is below 40^{o}F and another for summer installations when outside temperature is above 40^{o}F. The resin and the hardener are supplied separately in cans. The resin and hardener are pre-measured so that there is no need of calculating the mix ratio. The manufacture indicates that the material should be left to cure for approximately one hour before opening the site to traffic.

Table 1 compares pertinent material characteristics for the five adhesive types. The information in Table 1 was obtained from the technical data sheets provided by the manufacturers where available. It is noteworthy that information on two adhesives—that is P5G and AS475—are adaptation from a study conducted by Euber *et al.* (1994) since the technical data sheets from these manufacturers lacked the relevant information. Through a telephone conversation with manufacturer's representatives, they indicated that the material composition has not changed much since Euber *et al.* study was conducted.

Methodology

A research protocol was designed to evaluate the performance of piezos so as to recommend which adhesives would be suitable for Florida conditions. The protocol included (a) comprehensive literature search on the characteristics of epoxies, acrylics, and polyurethanes, (b) survey of the experience of State Departments of Transportation in the U.S. on the use of these adhesives for piezo installations, (c) laboratory testing of the approved adhesives, and (d) long-term field monitoring of ANOVA-designed experiments.

TABLE 1. Comparison of physical characteristics of the adhesives

Property	Adhesive type				
	G100	7084	P5G	AS475	PU200
Hardness	85-88	80±5			85
Shrinkage	0%	0%	0%	0.04%	
Water Absorption	0.03%	0%			
Compressive Strength	8000 psi		3583 psi	1024 psi	5173 psi
Tensile Strength		2500±200 psi	2564 psi	2529 psi	18811psi
Viscosity		500 poise	25 Pa-s	21 Pa-s	110 poise
Set time		45 min	11 min at 0^oC	30 to 40 min	20 min
Gel Time	17-25 min. @ 77^oF	17 to 25 min.	13 min. @ 25^oC	17 min. @ 25^oC	10 min. @ 20^oC

Findings

The materials studied can be categorized in three main groups—epoxies, polyurethanes, and acrylics. Different sources that were used to examine each type of bonding materials i.e., literature review, state experience survey and laboratory testing suggest that there are distinctive properties associated with each material. The following discussion is a synthesis of information found from various sources and would build a basis for the recommendations about to be made.

Epoxies
The laboratory results shows that epoxies are associated with hardness behavior, high compressive strength, with high modulus of elasticity. No significant difference was observed between epoxies and other types of materials. The epoxies were also found to have relatively higher peel strength with an exception of Bondo 7084. The epoxies also resulted with higher peel strength. However laboratory results suggested little flexibility of epoxy materials with exception on E-Bond 1261.

The state survey respondents commented on some epoxies. The respondent from the State of Connecticut reported that G100 performed well in concrete pavement installations while it developed cracks when sensors were installed in asphalt pavements. The State of Utah reported that it had used G100 in the past but it failed in the first summer after installation. The State of West Virginia also reported that at numerous sites installed with G100 cracks were observed. The State of Nebraska reported that 7084 adhesive was very stiff during installation but had minimum cupping and weather effects. The State of Kentucky reported that 7084 adhesive did not have good long term bonding characteristics. E-Bond 1261 was not in use around the country at the time of this study, therefore there was no information about the product from states' survey.

Polyurethanes
As with epoxies, the laboratory results showed that polyurethanes are associated with hardness behavior but with lower compression strength and modulus of elasticity. The results further

suggest that polyurethanes have the lowest peel strength among the rest of the materials. PU200 is the only polyurethane material that was reported to be used by some states. The respondent from the State of Virginia said that PU200 has not performed well in the state and he suspected that the material could be suffering from long-term creep and stress relaxation problems. In addition, according to one FDOT contractor, eighteen sites in Ohio installed with PU 200 have failed. The contractor suspects that part of the problem with PU200 is excessive shrinkage, which affects bonding between the sensor and the adhesive.

Acrylics

Contrary to epoxies and polyurethanes, laboratory test results suggested that acrylics are softer than epoxies and polyurethanes. The laboratory results also indicated that acrylics have lower compressive strength, lower modulus of elasticity and moderate strain hence reasonably more flexible than epoxies and polyurethanes, with an exception of E-Bond 1261. While P5G and P6G resulted in relatively lower peel strength, AS475 resulted in higher peel strength than some polyurethanes and epoxies.

Several states reported on performance of acrylics (P5G and AS475). The State of Kentucky reported that P5G had good long term bonding characteristics while Colorado surmised that since switching to P5G from other adhesives, the failure rate of piezo installations has been greatly reduced. The State of Montana reported that they have been pleased with the performance of P5G since most of the failures have been in cabling, sensor itself, and pavement, but generally not the adhesive. However, Montana also reported that they noticed that when P5G is installed in pavements with thin overlays it generally tends to fail prematurely. The State of Washington reported that using AS475 has greatly reduced their piezo installations failure rate. Likewise, the State of Utah reported that the field crew prefers AS475 over PU200 since it mixes and pours well, as well as it cures quicker than PU200. The study by Euber *et al*. (1994) also found that acrylic-based adhesives performed better than epoxies in most cases during the field trials.

Recommendations

The preliminary recommendations on the type of adhesives to be used in Florida are based on the review of literature, contact with various state personnel and technicians, survey of different states' practices, review of manufacturer's own technical data sheets, and the laboratory test results. The recommendations are termed preliminary since long-term performance monitoring of the recommended grouts in the field is needed to ascertain their suitability for Florida environmental and traffic conditions. A prolonged field monitoring will also lead to recommendation of test procedures and material specifications to be used in approving future adhesives submitted by manufacturers for review by FDOT. These recommendations are related to adhesives used only in installation of sensors in asphalt concrete pavements.

The research results summarized above indicate that acrylic-based adhesives generally have better performance characteristics compared to epoxy and polyurethane-based adhesives. Acrylics tend to have characteristics similar to flexible pavements, i.e., good impact resistance and flexibility. In addition, the research results indicated that acrylics also have reasonable peel and shear strength. These characteristics were also confirmed by a study conducted in Texas by Euber *et al*. (1994). This study found that acrylic-based adhesives performed better than epoxies in most cases during the field trials. Likewise, numerous states that have used adhesives extensively report a reasonable degree of satisfaction with the performance of acrylic-based adhesives in flexible pavements.

The difference in performance of acrylics compared to epoxies and polyurethanes can also be explained by considering the glass transition temperature of these materials. Increased stiffness at low temperature may result in cohesive failure of the adhesive. At very low temperatures, the adhesives become very rigid (glassy region) as shown in Figure 1. The rigidity is represented by a high modulus of elasticity. After reaching the glass transition temperature, T_g, the increase in temperature results into a rapid decrease in modulus of elasticity. Eventually, a point is reached beyond which the modulus of elasticity remains relatively constant as the temperature increases (rubbery region).

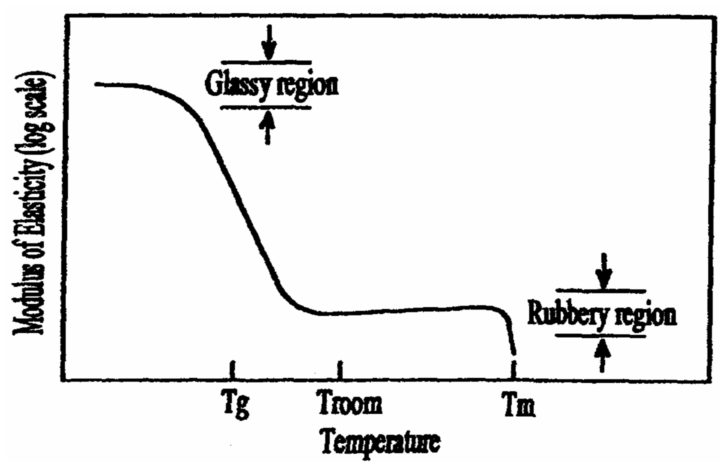

FIGURE 1. Variation of Modulus of Elasticity with Temperature (Rogers *et al.*, 1999)

Figure 1 suggests that a good adhesive material for application with flexible pavements should have a low glass transition temperature, T_g. The brittleness and rigidity of epoxy and polyurethane-based adhesives suggest that they do have a high glass transition temperature and thus they become more brittle than acrylics at temperatures between T_g and T_{room}. This phenomenon might partially explain lack of good bonding characteristics of epoxies and polyurethane adhesives used in colder regions of the United States.

Based on the literature review, state survey and laboratory test results it is recommended that the Florida Department of Transportation should use acrylic-based adhesives with increasing frequency in the installation of piezoelectric axle sensors in asphalt concrete pavements. The two acrylic-based adhesives are IRD AS475 and ECM P6G. The IRD AS475 is currently in the approved product list. The ECM P6G is not in the approved product list and therefore should be added. As for epoxy-based material, it is recommended that E-Bond 1261 should be added to the approved product list given that during the laboratory tests, the material displayed a number of properties that may be suitable for installation of piezoelectric axle sensors in asphalt concrete pavements. However, the material should be carefully monitored in the field to determine its long-term performance characteristics.

It is further recommended that ECM P5G, PU200 by Global Resins Limited, and Bondo 7084 should be removed from the approved product list. The manufacturer of P5G, i.e., Electronic Control Measurement (ECM), has reformulated this material to increase its workability. The material is now called ECM P6G following this reformulation and has been recommended for inclusion in the approved product list as noted above. The PU200 and Bondo 7084 material displayed a number of characteristics unsuitable for use in Florida environment. In addition, the states' survey results showed that many states had negative experience with these two products. In the middle of the laboratory evaluation, the Global Resins Limited submitted PU260 for evaluation and it was found that it displayed negative characteristics similar to PU200. It is therefore recommended that PU260 should not be approved for use in Florida. The above recommendations are summarized in a tabular format shown below.

Product	**Recommendation**
IRD AS475	Approve
ECM P6G	Approve
E-Bond 1261	Approve
ECM P5G	Discontinue
PU200	Discontinue
Bondo 7084	Discontinue
PU260	Disapprove

Chapter I

INTRODUCTION

1.1 Overview

The main goal of this research project was to develop test procedures that can be used to test adhesives for installation of piezoelectric axle sensors in the State of Florida. In addition, this research undertaking was also aimed at developing material specifications that will be used to select adhesives to achieve long-term field performance of piezoelectric axle sensors. The study was prompted by the fact that there are no standard procedures locally and nationally for testing adhesives and no state has so far developed material specifications for adhesives specifically for use in piezoelectric sensor installation.

Long-term observation of sensor performance in Florida suggested that the use of adhesives with characteristics unsuitable for Florida traffic, pavement, and environmental conditions might be contributing to premature failures of piezoelectric sensors. The excessive failures of piezos installed at temporary and permanent telemetered traffic monitoring sites (TTMS) is of major concern to the Florida Department of Transportation (FDOT) because of the high cost of replacements and the attendant disruption of traffic flow. The following sections further discuss the nature of the problem, the results of the research undertaken so far, followed by a preliminary recommendation of types of adhesives that seem to perform better based on synthesis of research results so far compiled.

1.2 Use of Piezoelectric Axle Sensors in Florida

Piezoelectric sensors are widely used by the Florida Department of Transportation for collection of traffic data that includes volume, speed, and vehicle classification. Piezoelectric sensors are also used by the Department at weigh-in-motion sites to capture individual axle weights. The majority of piezoelectric sensors installed in Florida are for axle counts while the rest are for weigh-in-motion. The piezoelectric sensors are installed at both portable and permanent count stations. The Florida Department of Transportation Planning Office in Tallahassee operates close to 322 permanent continuously operating sites that collect traffic information throughout the year. These sites are known as telemetered traffic monitoring sites (TTMS). Of the 322 sites, 205 sites have piezos installed for axle classification, and 39 sites have weigh-in-motion capabilities. The remaining sites have only loop sensors installed to capture vehicular volumes and speeds.

In addition, some of the eight districts of the Florida Department of Transportation use permanently installed piezos at portable sites. Though the exact count of existing temporary TTMS sites could not be ascertained, a cursory review shows that there are approximately 770 piezos installed at these sites. It is estimated that the piezo installations, on the average, last approximately 4.9 years with the common type of failures being lack of signal output. Furthermore, it is estimated that approximately 169 piezos fail each year (2000-2001 records).

The average cost of replacing piezos at one TTMS site is estimated at $1,700. Thus, it costs FDOT approximately $29,000 annually to replace failed piezo sensors. The high cost of replacing piezos underscores the need to develop new test procedures and installation practices that would improve performance and durability of piezos at TTMS sites.

1.3 Principle of Operation of Piezoelectric Axle Sensors

As indicated above, piezoelectric axle sensors are used to collect traffic data such as vehicle counts, vehicle classification, and speed measurements. The piezoelectric sensor consists of a long strip of piezoelectric that is imbedded in a pavement. When a vehicle passes over it, compressing the piezoelectric material, a voltage is produced and recorded by the automatic data recorder (ADR). The piezoelectric sensor has the advantage that it records exactly where and when a vehicle passed by because it is a line sensor installed perpendicular to the path of the vehicle. A series of two of them installed at a predetermined spacing may be used to measure a vehicle speed. Figure 1-1 shows such installation arrangement on TTMS Site 9936 on Interstate 10 west of Lake City.

FIGURE 1-1. Piezoelectric Axle Sensor Installed at TTMS # 9936

1.3.1. How piezoelectric sensors are installed

Piezo installation depends on whether the installation is intended to be temporary or permanent. If the sensor is installed for temporary purposes a thin piezoelectric strip is laid across the top of the pavement in a similar fashion to pneumatic road tube counters. Permanent installation of piezoelectric sensors requires cutting a groove in the pavement of sufficient depth and breadth to accommodate the sensor. An adhesive material is poured into the groove, encapsulating the sensor. The polymerization of the adhesive ensures that the sensor is held in place. In the past, most sensors were cast into an aluminum channel that was held into the pavement by an epoxy binder. However, because this required a much bigger groove, the practice has been discarded in favor of a bare sensor. Both sensors approved by the Florida Department of Transportation Planning Office—that is, Roadtrax BL sensor manufactured by Measurements Specialties Inc. (MSI) and Vibracoax (a.k.a. Thermocoax) sensor manufactured by Phillips Electronic Instruments Company—are of the latter type.

Figure 1 shows a typical groove size recommended by MSI for BL sensor installation. Closer examination of Figure 1-2 indicates that there are many factors that might affect the performance and durability of the piezo. These factors include the type of pavement and its site characteristics, sensor and adhesive characteristics, quality of installation, and environmental and traffic conditions at the site. The following section discusses some of these factors in detail.

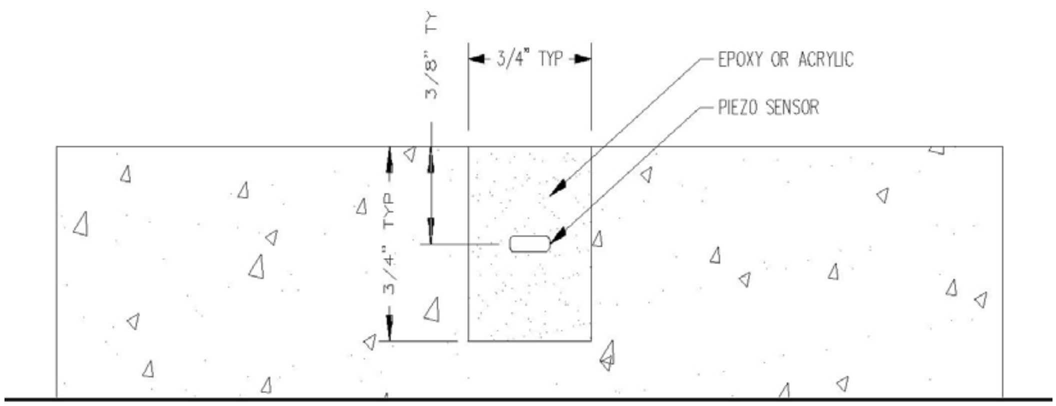

FIGURE 1-2. Typical groove size for BL sensor

1.3.2. Factors affecting performance and durability of piezoelectric axle sensors

In general, performance, durability, and ultimately the failure of a piezoelectric sensor will depend on the design of the sensor, site characteristics and pavement material type, quality control during installation, and characteristics of the adhesive material. In addition, the interaction of these variables with traffic and environmental factors such as temperature and moisture can also lead to premature failure of the installation. The major factors affecting long term performance and durability of piezoelectric sensor installations are discussed below.

1.3.3. Type of pavement and site characteristics

The type of pavement has been observed to affect the signal output and durability of a sensor installation. Sensors tend to last longer in rigid pavements than in flexible pavements. Also, with certain sensor designs, flexible pavements tend to generate more bow waves than rigid pavements. The site characteristics that might positively affect the performance and durability of an installation include level pavement with good drainage characteristics, structural and functionally sound pavement with no cracks or localized deformations. Installation of piezos at sites that have localized depressions such as rutting can lead to premature failure. Excessive rutting in asphalt pavements, for example, may cause the sensor to become partially loose, causing vibrations that degrade the accuracy of the sensor reading, failure of the adhesive-pavement bond and water intrusion. In addition, pavement rutting can cause uneven reading across the sensor profile.

1.3.4. Quality control during installation

The performance and durability of piezos can be influenced by quality control during installation. There are several phases of piezo installation ranging from material handling, groove cutting, laying of the piezo strip into the cut slot, mixing of two-part adhesives, pouring of the adhesive, and the curing process prior to opening to traffic. The size of the groove in terms of depth and breadth can have many implications one of which is the effect on polymerization. Since the depth of cure is restricted by the heat that is naturally generated during cure reaction, in some cases the temperature can rise high enough to burn or damage the substrate. The cure of two-part adhesives can be accelerated using heat, although cure temperature can adversely affect the cross-link density and modulus of elasticity of the cured adhesive. Adhesives selected and qualified for room temperature curing should be requalified if a heat-cure step is added. Varying the type and amount of the hardener can also control the cure rate of adhesives supplied in two parts.

3.2.5. Material characteristics

The material characteristics are those related to the sensor and adhesive. The sensor design and surface characteristics can have influence on output signal and the quality of bonding to the adhesive. The surface preparation of the sensor is a critical step in the bonding process, regardless of which adhesive is used. To a great extent, bond strength is determined by the degree of adhesion between the sensor surface, the adhesive material and the substrate. The literature indicates that for a brass sensor, such as the BL sensor, to bond well with any adhesive it needs to be degreased, abraded, and degreased again. Degreasing is done to remove all traces of oil and grease as well as fine particles resulting from abrading. Lightly abraded surfaces give a better key to adhesives than do highly polished surfaces. The abrading of brass surfaces can be accomplished by emery cloth or grit-blast. The adhesive characteristics are discussed in detail in the next chapter.

Chapter II

LITERATURE REVIEW

2.1. Overview

A polymer is a compound formed by the reaction of simple molecules having functional groups that permit their combination to proceed to high molecular weights under suitable conditions (Sharpe, 1999). Polymeric materials usually have high strength, possess a glass transition temperature, exhibit rubber elasticity, and have high viscosity as melts and solutions (Kumar and Gupta, 1998). It is due to these unique properties that they have found multifarious application to mankind in our modern society. Polymers that are commonly used for construction and highway installation include acrylics, epoxies and polyutheranes.

The installation of piezoelectric sensors for vehicle axle classification requires a better understanding of the composition and performance of three components—that is, the pavement, sensor, and bonding material. The bonding material (a.k.a. grout, adhesive, or sealant) is a substance that is capable of holding materials together by surface attachment.

2.2. Previous Evaluation of Bonding Materials for Piezo Installation

The literature review showed that little research has been done in adhesives used in installation of piezoelectric sensors. One study that report on the bonding materials for piezoelectric sensors was conducted by Ueber *et al.* (1994). The study reported on the physical characteristics of the bonding agents including epoxies and acrylics. The studied materials included Flexibond #11, Flexolith and Transpo T46 (Flexible epoxies), Schul and TXDOT G-100 (rigid epoxies) and P5G and IRD (acrylics). Other materials tested were (HMMUP) High Molecular-weight Methacrylate and recycled Unsaturated Polyester and Masterfill, which are neither acrylics nor epoxies.

The study tested the bonding materials for different mechanical, physical and compatibility tests. The mechanical properties tests included bond strength, flexural bond test, shear bond test, tension bond test and freeze/thaw tension while physical tests performed were gel time, shrinkage, thermal expansion, vicat set time and viscosity. Compatibility tests performed included bond strength, flexural bond test, shear bond test, tension bond test and freeze/thaw tension. Since the objective of the study was to determine the best bonding materials, the study recommended some tests for the selection criteria while some of the mentioned tests were not recommended. The recommended tests and values are summarized in Table 2-1.

The same study conducted field evaluation of the materials. The results showed that at all three test sites both ECM P5G and IRD AS475 had good workability, smooth flow that encapsulates the sensor, and fast curing time. However, the study shows that both ECM P5G and IRD AS475 showed signs of deterioration during the winter at the Amarillo site due to prolonged cold temperatures. Although a different criterion was used for evaluation of binder materials in the Texas study, ECM P5G and IRD AS475 were found to be among the materials with low glass transition temperature. However, it should be noted that some materials that were ranked low also had low glass transition temperature.

TABLE 2-1. Recommended Selection Criteria According to Ueber *et al.* (1994)

Recommended Test	**Required Result (1 psi = 6.9 kPa)**
Compressive Strength	≥ 1,000 psi
Complex Shear Modulus – Storage Modulus G'	2,000 – 10,000 psi at 25o C (77o F) Decrease with increasing temperature
Gel Time	5 to 15 minutes
Shrinkage	-1.0% to 0.5%
Vicat Set Time	≤ 30 minutes
Viscosity	20 to 40 Pa-s
Bond Flexural Strength	≥ 100 psi (to asphalt) ≥ 300 psi (to concrete) Failure at least 50% in paving material
Field Trial (ease of use)	

Another study that evaluated adhesive materials similar to the ones approved by FDOT was conducted by Alavi *et al.* (2000). This study was designed to evaluate, among others, the effect of adhesive material on stress transfer and signal output of weigh-in-motion sensors. The results found that temperature had an effect on signal output since the increase in temperature caused a decrease in the stiffness of the pavement and adhesive; consequently, the amplitude of the raw signal increased. However, the most significant result of this study was that the four adhesives that were used with Class I BL sensor (ECM P5G, PU 200, E-Bond 1261 and IRD AS475), did not show any significant difference in signal output with the increase in temperature.

Literature search also revealed another study that evaluated Bondo 7084 adhesive. This study, sponsored by the Florida Department of Transportation and conducted by the Florida Institute of Technology was designed to evaluate the performance of fiber optic sensors buried in pavements. The study evaluated various adhesives for use as bonding agents. Only one of the adhesives that were evaluated as part of this study—that is Bondo 7084—is approved for use by the FDOT Planning Office through their approved product list. The study indicates that Bondo 7084 performed poorly at two sites where it was evaluated. The material became so soft that it stuck on vehicles wheels as they passed on the groove causing the material to peel off from the sensors (Criss 1998).

2.3. Types of Bonding Materials

All five adhesives discussed above are polymer materials that fall into three major groups: (a) epoxies (i.e. *G100* and *7084*), (b) acrylics (i.e., *AS475* and *P5G*), and (c) polyurethane (*PU200).* The general chemistry of epoxy, acrylic, and polyurethane polymers are briefly summarized below in relation to material constituents and known performance characteristics of these materials as adhesives and sealants.

2.3.1. Epoxies

Epoxy adhesives consist of an epoxy resin (binder) and a hardener. The resin, usually in semisolid state, is the principle component and a hardener is a substance added to the adhesive to promote the curing reaction. The curing temperature strongly influences the ultimate cross-link density. The supply of heat during curing increases molecular mobility resulting in higher cross-link density.

Epoxies have found a particularly wide use in the construction industry. Amstock (2001) indicated that epoxies have high resistance to corrosion and chemicals. However, epoxies tend to be very rigid and generally exhibit low peel strength. These characteristics can become a problem in the bonding of materials to flexible substrates such as asphalt pavements. Toughening agents can be compounded into the epoxies to improve peel strength to some extent. Epoxies usually produce large amounts of heat upon curing, causing problems with heat-sensitive materials or substrates, particularly if large volumes of epoxy are used.

2.3.2. Acrylics

Acrylics are thermoplastic materials manufactured from methylacrylate monomers found in products of petroleum, agricultural, and synthesis industries. Acrylics adhesives cure by addition of polymerizing agents. The formation of free radicals initiates a very rapid chain reaction that results in the cure of the adhesive. This cure chemistry is significantly more rapid than a typical cure for condensation polymers such as those in epoxy and urethane adhesives

Acrylics challenge epoxies in shear strength and offer flexible bonds with good peel strength. Acrylics are known for their high impact resistance, good low temperature characteristics, excellent long-term resistance to weathering and sunlight, low water absorption and excellent resistance to most chemicals. While acrylics respond well to heat, they are not affected by cold, and they do not become brittle in cold weather.

2.3.3. Polyurethanes

Like epoxies, polyurethane reactive adhesives include systems that are available as 100% solids or solvent based on one or two part formulations. Polyurethane adhesives are made with isocyanate resins as building blocks. The pot lives of two-component polyurethane adhesives such as PU200 can vary from as little as 15 seconds to as long as 16 hours, depending on the type of reactant (or hardener) used. Polyurethane-based adhesives form tough bonds with high peel strength. They have better low temperature strength than other adhesives but do not have high temperature resistance. They also have good flexibility, abrasion resistance, and toughness. They have good chemical resistance although not generally as good as epoxies or acrylics. Some polyurethane adhesives degrade substantially when exposed to high humidity and high temperature environments. This moisture sensitivity occurs with both the cured adhesive and the uncured components. Kumar & Gupta (1998) pointed out that usually the curing is slow and the adhesive joint tend to have low modulus of elasticity.

Table 2-2 summarizes important properties of epoxies, acrylics, and polyurethanes. The table lists some of the major advantages and shortcomings of each type of adhesive as it relates to workability and long term performance of the adhesive when used outdoors as a bonding agent or sealant.

TABLE 2-2. Advantages and limitations of epoxies, acrylics, and polyurethanes

Type of adhesive	Advantages	Limitations
Epoxy	• High chemical resistant • Outstanding adhesion to various substrates • Water resistant • Low shrinkage upon cure • Good electrical properties • High strength	• Exact proportions needed for optimum strength • Limited pot life • Rigid
Acrylic	• Excellent impact resistance and flexibility • Excellent peel and shear strength • Substrate versatility	• Shorter working time
Polyurethane	• Excellent toughness and flexibility • Fair to good chemical resistant • Excellent UV resistance • Fast cure	• Poor temperature resistant • Sensitive to moisture both in cured and uncured state • Short pot life • Slow curing • Low modulus • Poor water immersion resistance • Variety of formulations can cause wide differences in performance

2.4. Characteristics of Adhesives Approved by FDOT Planning Office

The information obtained from the Florida Department of Transportation indicates that there are five adhesives that have been approved for use in the State of Florida. These adhesives are G100 by E-Bond Epoxies, 7084 by Dynatron/Bondo Corporation, P5G by Electric Control Measurements, AS475 by International Road Dynamics Inc., and PU200 by Global Resins Limited.

2.4.1. G100 by E-Bond Epoxies

G100 is an epoxy-based material that has variably been used in Florida for approximately 18 years for piezo installation and other purposes such as patching and placement of anchor bolts, dowels and pins in concrete surfaces. It is usually supplied in two parts, a resin and a hardener. The material is supplied in 11½, 26, or 46-pound containers. The resin and the hardener are mixed in 25 to 1 ratio by weight. The manufacturer technical data sheet indicates that the resin and hardener should be mixed within three to five minutes of opening the containers and poured immediately after mixing. The manufacturer's recommends curing time of one hour to 14 hours depending on the substrate temperature. Lower substrate temperature requires longer curing period while higher substrate temperature requires shorter curing time, thus allowing faster opening of the road to traffic. It should be noted that originally G100 was formulated for installation of heavy WIM frames in portland cement concrete pavements in Texas.

2.4.2. 7084 by Dynatron/Bondo Corporation

This is also an epoxy-based adhesive that is supplied in two parts—resin and hardener. Both the resin and a hardener are supplied in 12.6 pounds. The material is mixed in 1:1 ratio. The mixing time is not indicated in the technical data sheet. The data sheet does not indicate the mix cure time but indicates the gel time at 77^{o}F to be between 17 to 25 minutes.

2.4.3. ECM P5G by Electronic Control Measurement

This is an acrylic-based adhesive supplied in two parts—resin and hardener. The hardener is peroxide. ECM P5G is also mixed with fine filler material intended to improve bonding. The filler material commonly used is dry sand. The adhesive is supplied in 13.5 pounds containers. The manufacturer recommends that the resin should be premixed (without hardener) for four minutes or until the resin has a smooth/even texture. The hardener is then added and mixed for not more than one minute after which the binder is immediately used. The data sheet indicates that the expected cure times range from 20 minutes for 75^{o}F to 100^{o}F temperatures to 40 minutes for 40^{o}F to 50^{o}F temperatures.

2.4.4. AS475 by International Road Dynamics (IRD) Inc.

This adhesive is also acrylic-based and supplied in two parts—resin and hardener. The hardener is composed of benzyl peroxide organic (PBO) powder. The resin is supplied already pre-mixed with fine filler material that, according to the manufacturer, provides strength and consistency to the adhesive mixture. The filler material is made of fine aggregate and prevents the resin from cracking by serving as a heat sink for the significant heat created during the curing of the resin. The material is supplied in 39.6-pound pailS for 12-foot sensors and 22-pound pails for 6-foot sensors. The manufacturer recommends thorough mixing of resin and filler material prior to adding the hardener. The hardener is added in an amount that is dependent upon the ambient temperature and mixed with resin and filler for approximately two minutes. The manufacturers indicate that the mixture cures fully in 30 to 40 minutes.

2.4.5. PU200 by Global Resins Limited

This is a polyurethane-based adhesive that is also supplied in two parts consisting of resin and hardener. In addition, the adhesive is supplied in two versions—one for winter installation when outside temperature is below 40^{o}F and another for summer installations when outside temperature is above 40^{o}F. The resin and the hardener are supplied separately in cans. The resin and hardener are premeasured so that there is no need of calculating the mix ratio. The manufacturer data sheet indicates that the material should be left to cure for approximately one hour before opening the site to traffic.

Table 3 compares pertinent material characteristics for the five adhesive types. The information in Table 1 was obtained from the technical data sheets provided by the manufacturers where available. It is noteworthy that information on two adhesives—that is P5G and AS475—are adaptation from a study conducted by Euber *et al.* (1994) since the technical data sheets from these manufacturers lacked the relevant information. Through a telephone conversation with manufacturer's representatives, it was indicated that the material composition has not changed much since Euber *et al.* study was conducted in 1994.

TABLE 2-3. Comparison of physical characteristics of the adhesives

Property	Adhesive type				
	G100	7084	P5G	AS475	PU200
Hardness	85-88	80±5			85
Shrinkage	0%	0%	0%	0.04%	
Water Absorption	0.03%	0%			
Compressive Strength	8000 psi		3583 psi	1024 psi	5173 psi
Tensile Strength		2500±200 psi	2564 psi	2529 psi	18811psi
Viscosity		500 poise	25 Pa-s	21 Pa-s	110 poise
Set time		45 min	11 min at 0°C	30 to 40 min	20 min
Gel Time	17-25 min. @ 77°F	17 to 25 min.	13 min. @ 25°C	17 min. @ 25°C	10 min. @ 20°C

2.5. Forces Applied to Binders

There are varied forces that act on the binder that binds the piezo with the pavement. These forces can contribute to the degradation of the bonding. The forces are discussed in the following sections.

2.5.1. Cyclic loading

The binder material is subjected to cycling loading caused by the action of tires on the road. The environmental factors such as temperature also cause cyclic loading to the binder. Ashcroff *et al.* (2001) reported that the mode of failure in composite joints is heavily dependent on environmental conditions, with temperature variation having a significant effect. The moisture is also known to contribute to the deterioration of the mechanical properties of bonded joints with time (Ashcroft, et al, 2001).

2.5.2. Compression

As it is to the pavement, the binder is subjected to the induced compression stresses mainly caused by the action of tires. However, because of repeated dynamic loading from the traffic the failure is expected to ultimately yield below the normal ultimate compression strength. The binder also experiences compression due to contraction and expansion that occur due to sudden changes of weather.

2.5.3. Tension

Several factors such as expansion and contraction of the binder material may lead to tensile stresses in the binder material and bond interface. Sufficient bond tensile strength is therefore required in order to overcome tensile stresses that may be induced to the binder.

2.6. Possible Modes of Failure and Their Causes

The bonding material can fail in various modes due to statistic and dynamic stresses caused by loading and environmental factors discussed above. The following sections discuss modes of failure that can happen and the mechanistic reasons for the failures.

2.6.1. Bond failure

One of the most important parameters affecting the bonding effect of the binder is the adhesion of the binder to the substrate surface. Lack of compatibility is one of the factors that causes bond failure. Compatibility is the ability of two or more substances combined with one another to form a homogeneous having useful binding properties. Other factors that may cause bond failure include shrinkage and poor workmanship during installation and water intrusion. As far as bonding between the binder and metals is concerned, water is known to be the substance that causes the greatest problems in the environmental stability of adhesive joints (Knox and Cowling, 2000). Water entry may cause weakening by one or a combination of the following actions:

(a) altering the adhesive properties in a reversible manner, such as by plasticization,
(b) altering the adhesive properties in an irreversible manner either by causing it to hydrolyse, crack or craze, and
(c) attacking the interface, either by displacing the adhesive or hydrating the metal or metal oxide.

2.6.2. Fatigue failure

More than 75 percent of failures in engineering components are attributed to fatigue failure (Timings, 1999). A material which is subjected to a stress which is alternatively applied and removed a very large number of times, or which varies between limiting values, will fracture at a very much lower value of stress than in a normal tensile stress. Alternate wheel loading, temperature variations, strong sunlight (UV radiation), ageing, expansion and contraction may attribute to fatigue failure of the binder.

2.6.3. Failure due to Compression

This mode of failure occurs when the applied stress exceeds the ultimate compression strength of the binder. However the design of the pavement is not based on the single impact load but rather accumulation of the effect of the long term axle loading. The understanding of the compression characteristics of the material is therefore not sufficient to describe long term performance of the binder in the pavement.

2.6.4. Failure due to brittleness

Brittleness occurs mainly in low temperature conditions. This is a property of the material that shows little or no plastic deformation before fracture when a force is applied. This type of failure is likely to occur if the temperatures are low.

2.6.5. Surface wearing

The binder surface is exposed to friction of tires that may lead to wearing of the binder layer hence exposing the sensor. The binder is also subjected to abrasion, a process where hard particles are forced against and moved along a solid surface. Hard particles may include sand, loose aggregates, metal chipping, etc.

Chapter III

LABORATORY TESTING OF THE BONDING MATERIALS

A number of laboratory tests were performed to determine the performance of the materials used for installation of piezoelectric sensors. The tests performed were aimed at examining the performance of these materials during working time and the materials resistance under subjection to different forces while the material is in service.

The American Society of Testing and Materials (ASTM) tests standards were adapted for testing materials used for installation of piezoelectric sensors. Due to the fact that there is not specific ASTM standard test for testing heat transfer behavior between the sensor and the grout materials and the asphalt and grout material, a specific test was designed to address this particular behavior. The tests that were performed are explained in the following sections.

3.1. Vicat Setting Time

The Vicat set time is used to estimate the initial setting time of materials and was conducted according to the American Society of Testing and Materials (ASTM) standard number 191-99. The test uses a needle of standard dimensions and weight. The test was conducted in a temperature-controlled room at 72^{o}F. The needle was dropped from a set height into the curing material at regular intervals. Penetration of the needle was measured at one-minute interval until no further penetration was observed. The material is considered set when the needle no longer penetrates the material. This time is recorded as the Vicat setting time. The test results are shown in Figure 3-1.

FIGURE 3-1. The Vicat Test Apparatus

The results in Figure 3-2 shows that G100 has by far the longest setting time, i.e. approximately one hour. This result suggests that a site installation that uses G100 as a grout cannot be opened to traffic in less than an hour to avoid damage to the uncured installation. Figure 3 further shows that the acrylic-based adhesives—that is, P5G, P6G and AS475—have almost similar setting times, 13 minutes, 16 minutes and 19 minutes respectively. Both P5G, P6G and AS475 use the same type of hardener, i.e. benzoyl peroxide organic powder. The difference in setting time might be due to the amount of hardener specified by the manufacturer. P5G manufacturer suggests the use of more hardener for the same amount of resin compared to AS475; thus speeding up the setting time. The results further indicate that P6G takes slightly more time to set as compared to P5G. This may be attributed to modifications that were made in P6G in order to improve its flowing properties for workability purposes. It was also noted that Ebond 1261 takes considerable shorter time (15 minutes) as compared to G100. Both E-Bond 1261 and G100 are manufactured by E-bond Epoxies, Inc. It is worthy noting that at one time the test was done at 50^{o}F and the same grout, Ebond 1261 took more than 30 minutes to set as compared to 16 minutes at 70^{o}F.

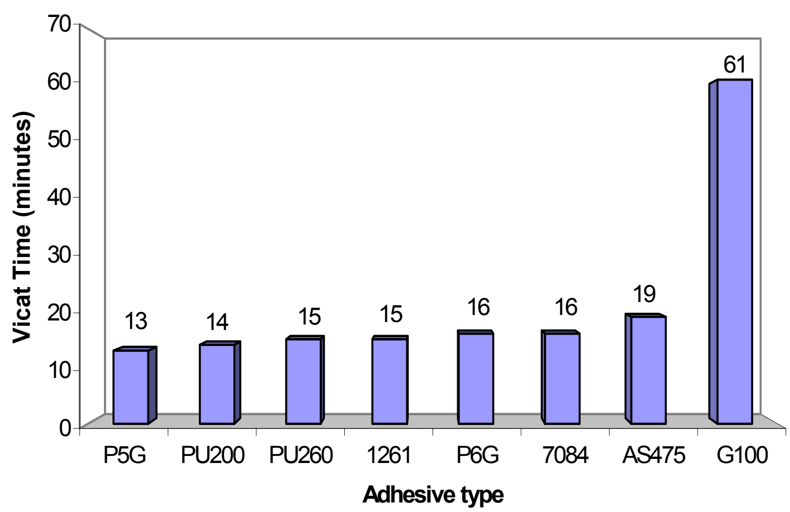

FIGURE 3-2. Vicat Setting Time Test Results

The vicat setting time obtained in the laboratory for P5G (13 minutes) is comparable to what was obtained from the technical data sheet. However, the value recorded in the technical data sheet for PU200 is 20 minutes, which is higher than 14 minutes obtained in the laboratory. It is possible that the values recorded in the data sheet are higher than the laboratory results because the test was done at 72^{o}F while the value recorded in the technical data sheet is for 68^{o}F. The technical data sheets for G100 and AS475 do not contain the values for initial setting times. However G100 manufacturer suggests two hours lapse before opening to traffic.

The results obtained from the laboratory tests seem to deviate so much from the values stipulated in the Bondo 7084 technical data sheet. The initial curing time reported by the manufacturers is 45 minutes while the value obtained from the laboratory was 16 minutes. It is possible a higher temperature condition used in the laboratory might have contributed to the difference.

3.2. Viscosity

The workability of an adhesive in an uncured state can be estimated by measuring its viscosity. The ASTM 3236 procedures were used in measuring the viscosity of the test samples. Viscosity is the term used to express the coefficient of internal friction resistance to fluid flow or mobility. A Brookfield digital rheometer shown in Figure 3-3 was used to measure the fluid parameter of shear stress and viscosity at a given shear rate.

FIGURE 3-3. Brookfield Digital Rheometer

A small sample of about 36.7 cubic inches was mixed and placed in a cylinder. The cylinder was then immediately placed under the viscometer before the sample started curing. A rotating spindle attached to the viscometer was then lowered into the material. Viscosity measurements were then read directly from the screen attached to the viscometer. It should be noted that different spindles are used for different ranges of viscosity. It was found that there was no appropriate spindle for measuring PU 200 mixture. However, its resin was measured. The introduction of the hardener in the PU 200 resin changes the viscosity significantly. The results of the viscosity tests are shown in Figure 5. Only PU200 and Bondo 7084 technical data sheets contain manufacture's suggested values for viscosity. However, Bondo 7084 reports separate values for the resin and the hardener, i.e., 500 and 1,100 poise respectively. PU 200 reports 270 poise and 86 poise for the resin and the hardener respectively.

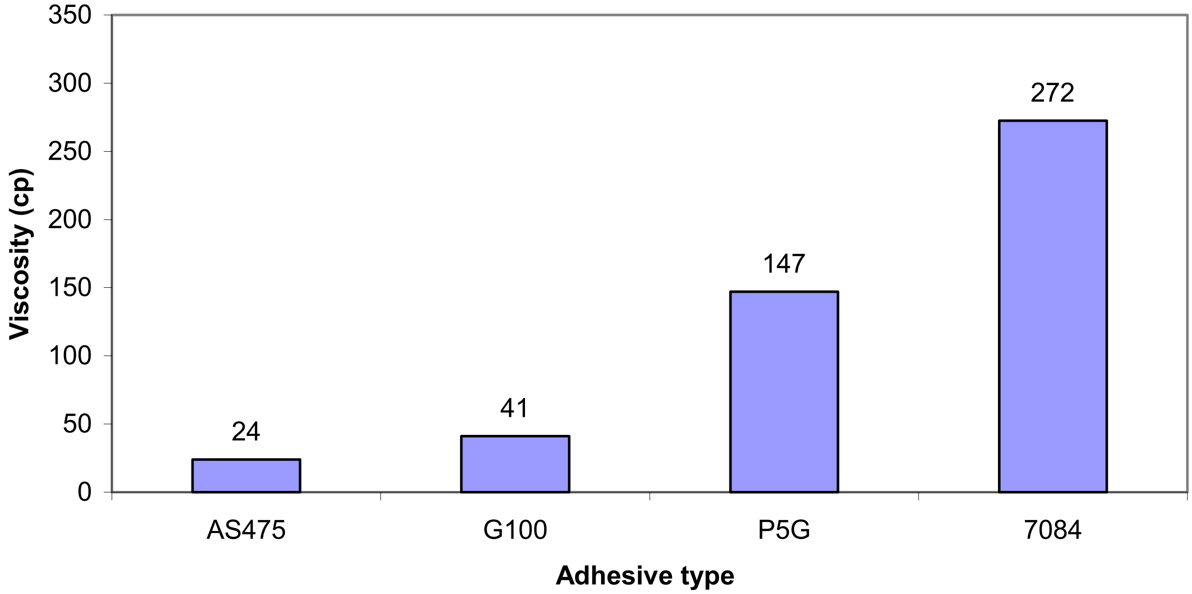

FIGURE 3-4. Viscosity Test Results

The results in Figure 3-4 show that Bondo 7084 is the most viscous adhesive of all the test samples. On the other hand, AS475 is the least viscous material suggesting that it does not flow as freely as Bondo 7084. Other adhesives had viscosity values that falls in-between Bondo 7084 and AS475. The technical data sheets give viscosity values for the resin and hardener separately. For Bondo 7084 the viscosity given by the manufacturer is 500 poise for the resin and 1,100 for the hardener. PU 200 gives 270 poise for the resin, 86 poise for the hardener and 110 poise for the mixture. The values for Bondo are given at 77^{o}F while those for PU200 are at 68^{o}F.

3.3. Water Absorption

Water absorption in a piezo installation can degrade the properties of the adhesive. The water absorption of the test samples was conducted in accordance with ASTM 570-98. Test specimens $\frac{1}{8}$-inch thick were made and then conditioned in the oven set at 110^{o}F for 24 hours. They were next cooled, weighed, and immersed in a container of distilled water maintained at 72^{o}F for 24 hours. At the end of 24 hours, the specimens were removed from the water one at a time and then all surfaces were wiped off with a dry cloth and weighed immediately. The water absorption value of each specimen was calculated using the following formula:

$$WaterAbsorption,\% = \frac{wetweight - conditionedweight}{conditionedweight}$$

Figure 3-5 shows the results of the water absorption test. The results in Figure 6 shows that there is no significant difference in water absorption between the test specimens. Technical data sheets for G100 and Bondo report the water absorption of 0.3% and 0% respectively. However, results show that Bondo 7084 has the highest water absorption value among the five tested products. The water absorption values for other products are not stipulated in their respective technical data sheets.

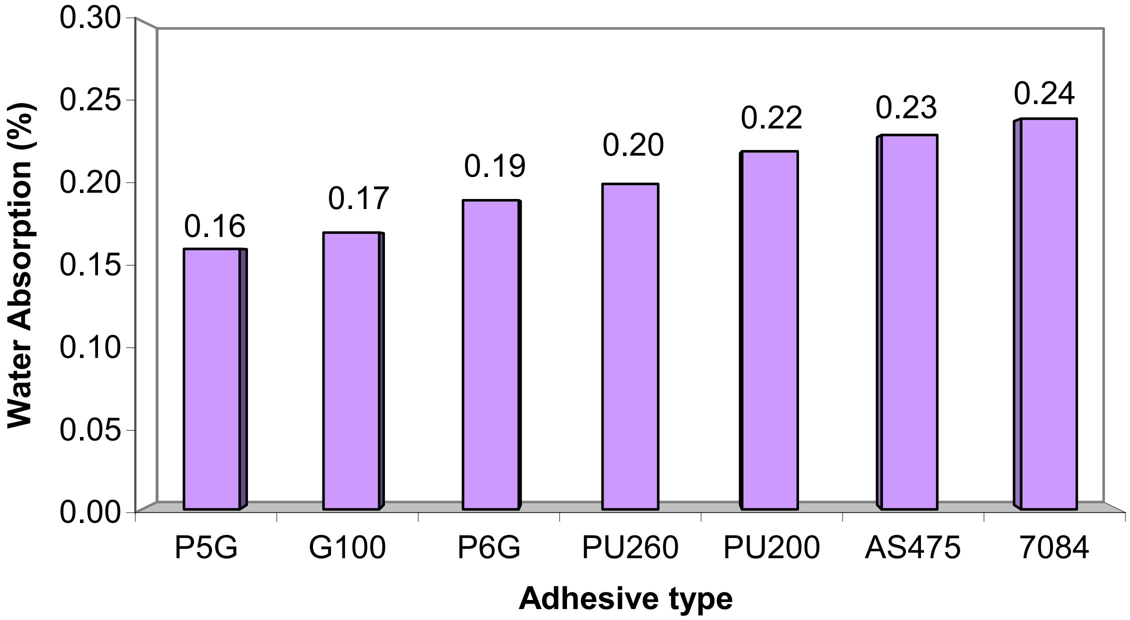

FIGURE 3-5. Water Absorption Test Results

3.4. Hardness

Hardness is defined as the ability of a material to withstand scratching or indentation by another hard body. Measurement of this property can only be relative to other materials and is given in the form of hardness number with no units. The hardness tests were conducted in accordance with ASTM D 2240-97. The test specimens of ½-inch were molded and were left to cure. The hardness of the specimens were measured at one hour and 24 hours after molding. The measurements were taken using Shore D hardness tester manufactured by Afri Systems Company. The Shore D Hardness Tester is shown in Figure 3-6. The prevailing temperature during the measurements was 72^{o}F. The results of the hardness tests are shown in Figure 8.

FIGURE 3-6. Shore D Hardness Tester

The results in Figure 3-7 reveal that G100 has the highest Shore D hardness after 24-hours. Comparison of 1-hr and 24-hr hardness values show that the acrylic-based materials—P5G and AS475—develop approximately 80 percent of their final Shore D hardness within one hour of molding. On the other hand, G100, PU200, and 7084 adhesives develop on the average only 35 percent of their final Shore D hardness value at 1-hr mark. The shore D values for 24 hours reported in the technical data sheets are 45 to 50 for P5G and 85 for PU200. The results also indicate that E-Bond 1261 develop 60 percent of hardness between the first 1 hour to 24 hours after casting.

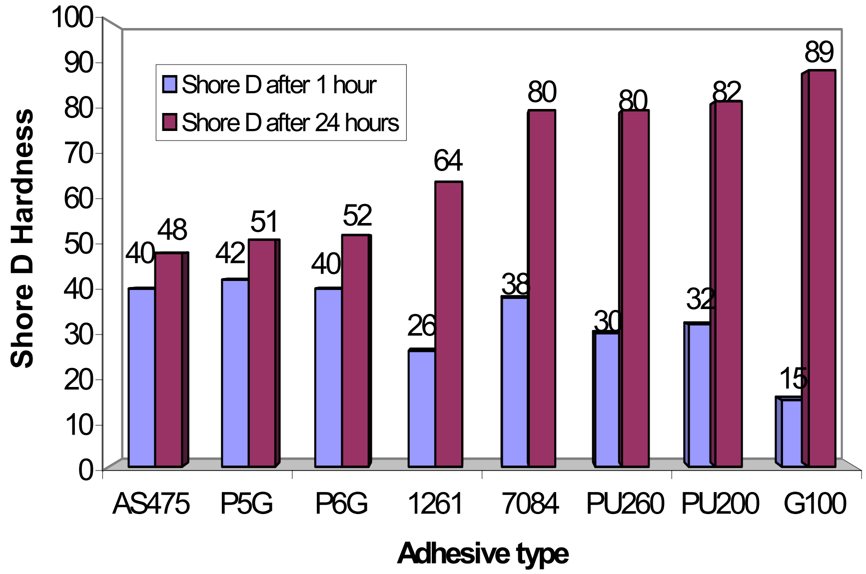

FIGURE 3-7. Shore D Hardness Test Results

3.5. Compressive Strength

Both the adhesive and the pavement are subjected to the same compressive stress induced by the traffic. The compressive strength of the materials will therefore give an indication of how much the material can resist the compressive stress caused by the traffic. The rectangular test specimens 1 x 1 x 2 inches were prepared in room temperature of 72^{o}F. Five specimens were tested for each material. The speed of testing was set to 0.05 in/min and the material compressed to fracture. The stress at fracture was then recorded. The setup of the test is shown in Figure 3-8.

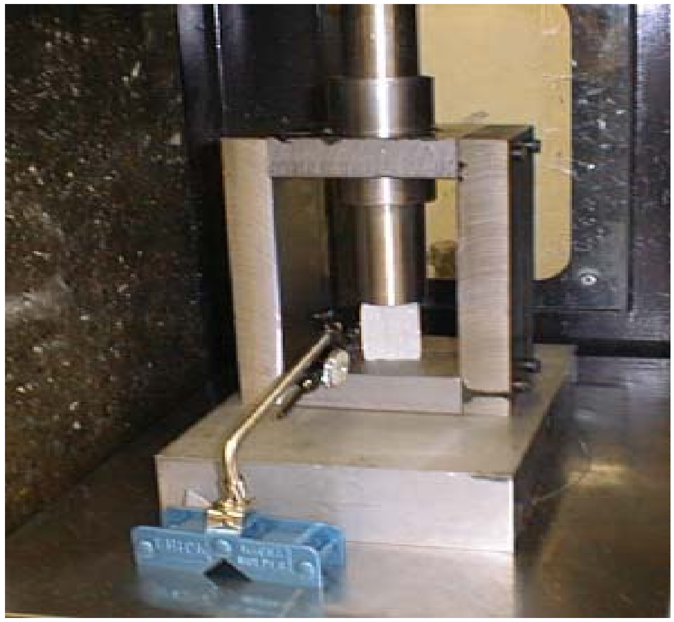

FIGURE 3-8. Compressive Strength Measurement Test Setup

The compressive strength test results shown in Figure 3-9 revealed that epoxies possess higher compressive strength as compared to acrylics and polyurethane. Bondo 7084 is the strongest material followed by G100 and E-Bond 1261. The results indicate that E-Bond 1261 has the lowest compressive strength among the epoxies tested. However, visual observation showed that the higher the strength the lower the flexibility with the exception of E-Bond 1261. Ueber *et al.* (1994) reported that generally the more flexible the material is, the lower its ultimate compressive strength. With an exception of E-Bond 1261 other materials that exhibited flexibility had low compressive strength values.

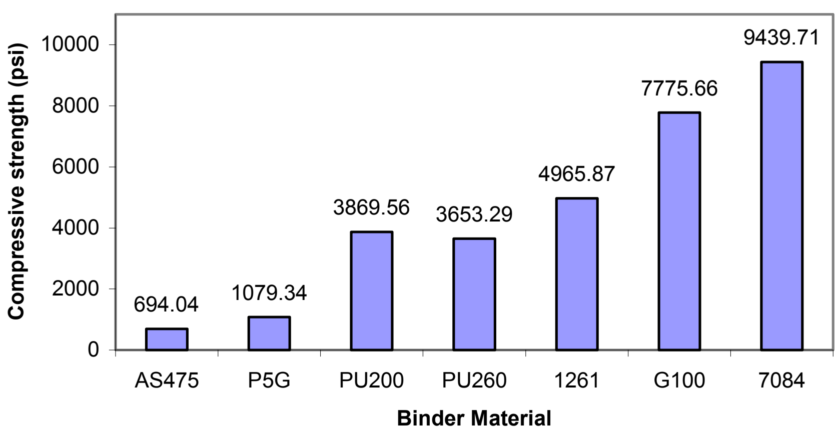

FIGURE 3-9. Compressive Strength Test Results

3.6 Modulus of Elasticity

In order to examine the flexibility of the tested materials, a strain gauge was fixed on the test setup in order to measure the deflection as the material is compressed. The final deflection was recorded at the point of failure. Modulus of elasticity was then calculated using the following equation:

$$Modulus = \frac{Stress}{Strain}$$

The results of the modulus of elasticity test are shown in Figure 3-10. While Bondo 7084 displayed the highest modulus of elasticity, AS 475 resulted with the lowest modulus of elasticity among all tested materials. In general, the high the modulus of elasticity the stiffer the material hence the less the flexibility. There must therefore be a tradeoff between high compressive strength and flexibility. It is worthy noting that E-Bond 1261 has considerable high strength with high flexibility. It is therefore important to perform field testing of E-Bond 1261 to examine its performance on site due to this peculiar property.

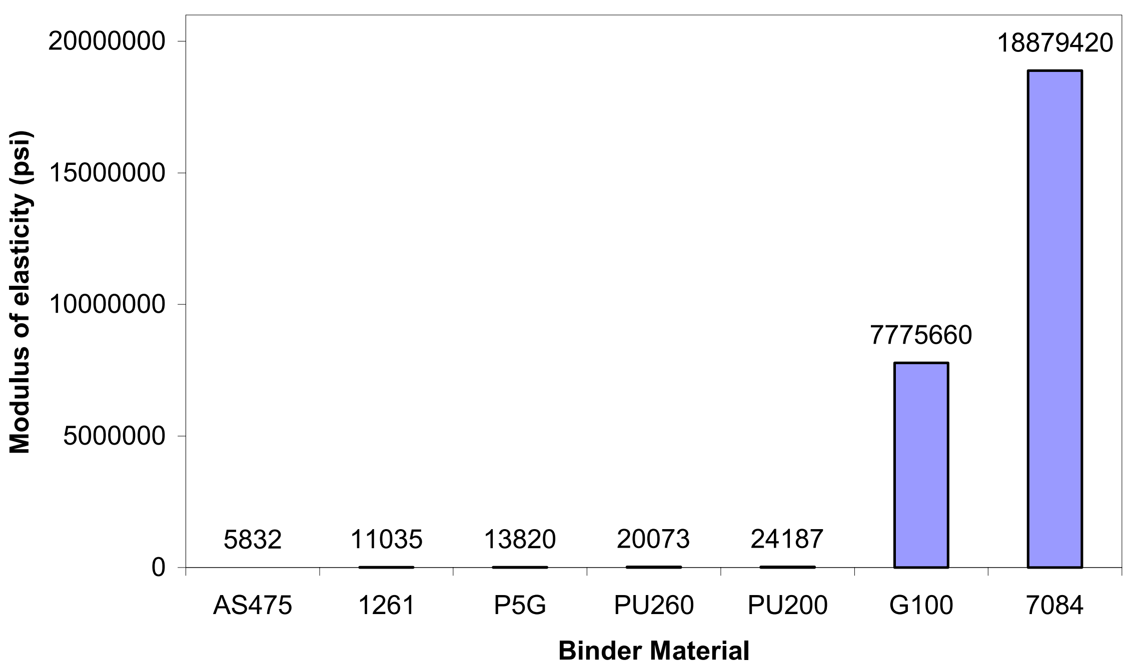

FIGURE 3-10. Modulus of Elasticity Test Results

3.7 Strain Measurement

Strain measurements are used to examine the change due to the load subjected to the material. The stain measurements are computed as the ratio of the length of the specimen after ultimate load to the original length (inches/inch). Generally, the higher the strain value the more flexible the material. In contrast, the lower the strain value the lower the flexibility hence brittle the material. The results show that E-bond 1261 is the most flexible material while Bondo 7084 is the least flexible bonding material among the tested materials (Figure 3-11).

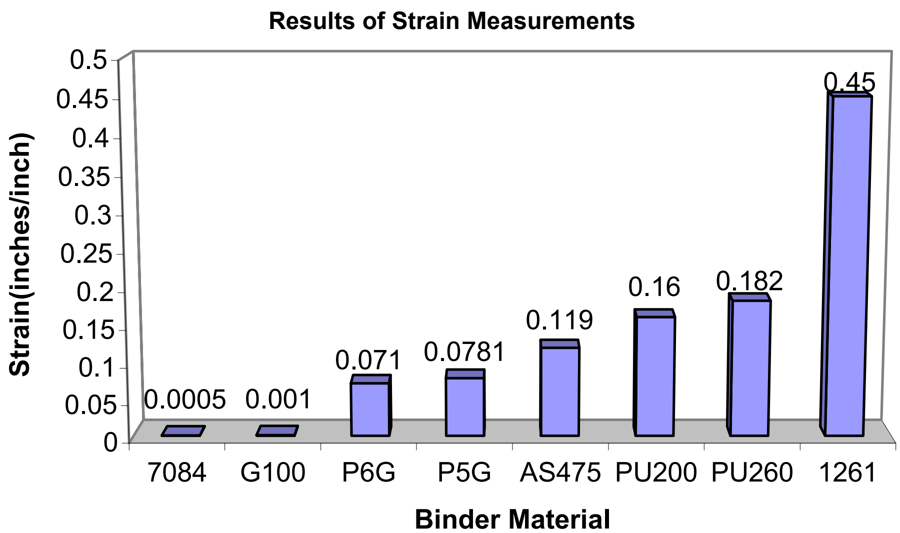

FIGURE 3-11. Modulus of Elasticity Test Results

3.8. Flexural Bond Strength Test

Flexural bond strength test was used to test the flexural bond strength of the bonding materials. The test is carried out to determine the flexural strength of joint between the asphalt pavement and the bonding material. This flexural test also called Modulus of Rupture tests or Third-Point Loading tests is normally performed using specimen beams that have been cast and cured. The strength of the bond under flexural loading is tested according to ASTM C 78-94. The specimen beams of the sample materials were prepared by casting them in a frame of required dimensions 8 inch x 2 inch x 2 inch as per the ASTM standards. Specimen molds constitute half part asphalt hot mix and half part sealant (Figure 3-12). It should be noted that the Hot Mix (S-I) of given specifications was to cast the asphalt.

Figure 3-13 shows the experimental set up. The results suggest that E-Bond 1261 has the strongest flexural bond strength (370 psi) while AS475 has the weakest flexural bond strength (360.95 psi). It should be noted that the range of the flexural bond strength results is small suggesting that there is no significant difference between the bonding materials.

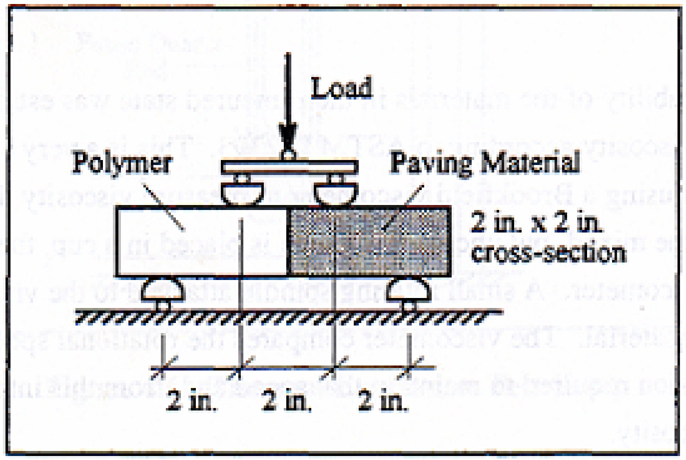

FIGURE 3-12. Flexural Bond Test Setup

The flexural bond strength is calculated by dividing moment at rupture by section modulus.

$$Fr = \frac{M}{S}$$

$$M = \frac{PL}{6}$$

$$S = \frac{bd2}{6}$$

$$\therefore Fr = \frac{PL}{bd2}$$

where *Fr* is the flexural bond strength, M is the moment at rupture, S is the section modulus, P is the maximum applied load indicated by the testing machine, L is the span length of specimen, b is the width of specimen, and d is the depth of the specimen.

FIGURE 3-13. Three Specimens Under Test

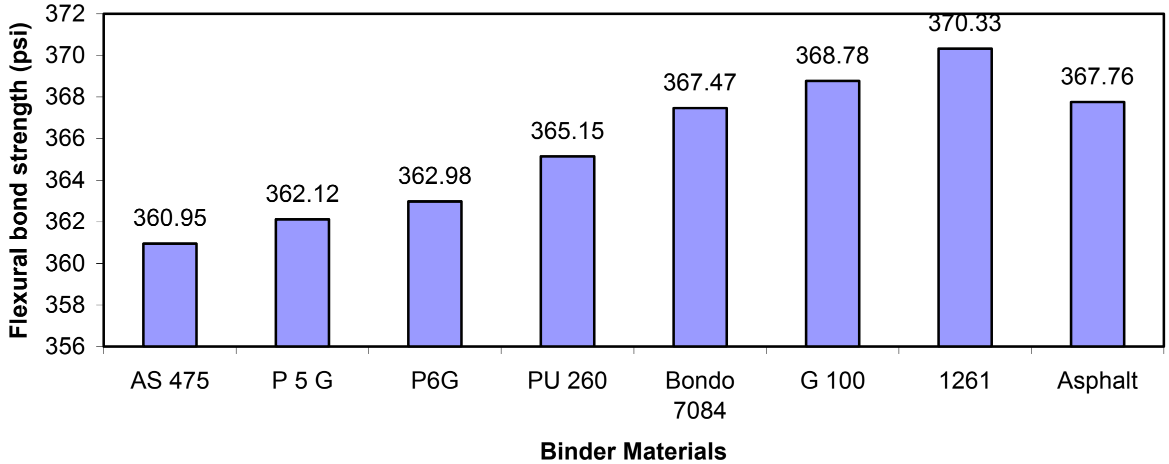

FIGURE 3-14. Results of Three Specimens Under Test

3.9. Peel Strength Test

The peel strength test was performed to measure the bonding between the adhesive and the pavement. The test was performed according to the American Society of Testing and Materials ASTM C 794. The peel force at failure was recorded by the computerized equipment using the Serial Acquisition System (SAS) shown in Figure 3-15.

FIGURE 3-15.Serial Acquisition System (SAS) Equipment

The results displayed in Figure 3-16 show that E-Bond 1261 has the highest peel strength while P5G has the lowest peel strength. The results also suggest that epoxies have the highest peel strength performance with an exception of Bondo. It is possible that the Bondo grout has relatively lower peel strength because of the bubbles formed at the interface of the two materials—grout and asphalt. Following the E-Bond products in peel strength was AS475 grout which failed at 146 pounds.

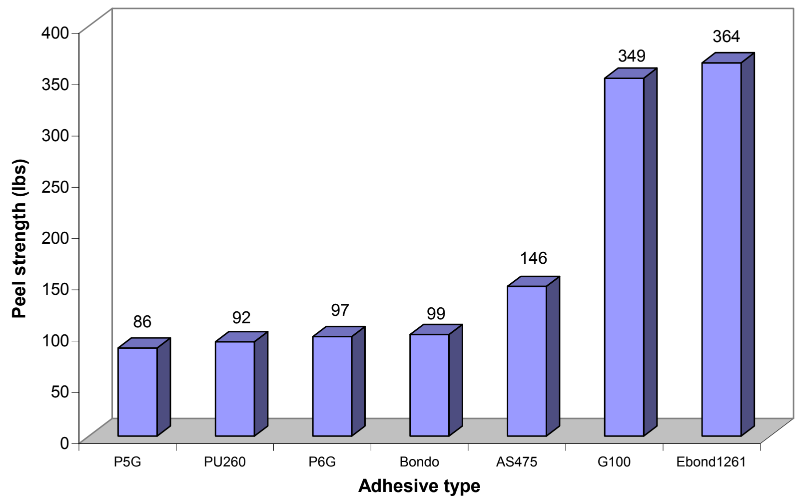

FIGURE 3-16. Peel Strength Test Results

3.10 Pull Out Test

The bond between the adhesive and the sensor was measured using a pull-out test developed for this project. According to the test, the sensor is inserted in the middle of the cylindrical mold when pouring the grout. The grout is left to fully cure before the test is performed. The sensor is pulled out from the grout using the loading frame and the results recorded using the computerized system using the Serial Acquisition System software (SAS) integrated to the pulling machine. Figure 3-17 depicts the experiment setup.

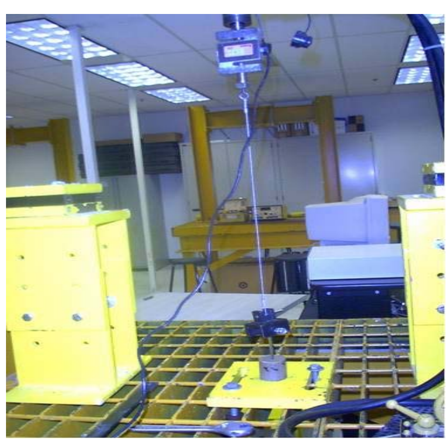

FIGURE 3-17. Pull Out Test Setup

The results in Figure 3-18 show that G100 provides the best bond with the sensor while the lowest load is required to pull-out the sensor from P5G grout. It was also observed that for G100 and PU260, the sensor failed before the ultimate bonding pull-out force was reached. In order to evaluate the influence of sandpapering in increasing the bond between the sensor and the grout material the some sensors were cast without being sandpapered while some were sandpapered (polished). Although the results show sandpapering causes a slight increase in pull-out strength for P5G, P6G, AS475 and Bondo 7034, the increase in strength was not that significant.

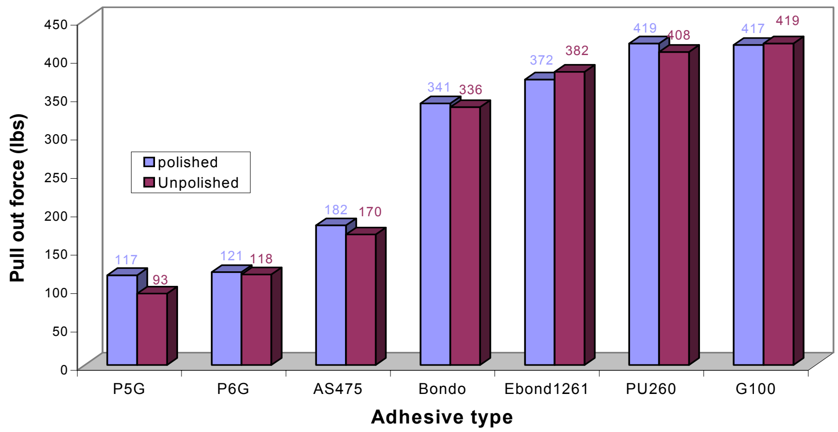

FIGURE 3-18. Pull Out Test Results

3.11 Heat Transfer Test

The heat transfer test was conducted to determine heat transfer characteristics of the grout materials. The sensor was cast in the grout which was embedded in the asphalt mould to mimic the site conditions. The thermocouples were connected to all the materials to measure temperature of each material with time. The Oven and Omega 8 voltmeter were used for conducting the heat transfer test. The results displayed in Figure 3-19 suggest that E-Bond 1261 has the best insulating properties while Bondo 7084 transmits more heat to the sensor. Field observations have shown that sensor outputs at high temperature are different compared to normal temperatures. It is therefore important that the grout material to have less ability to transfer heat to the sensor.

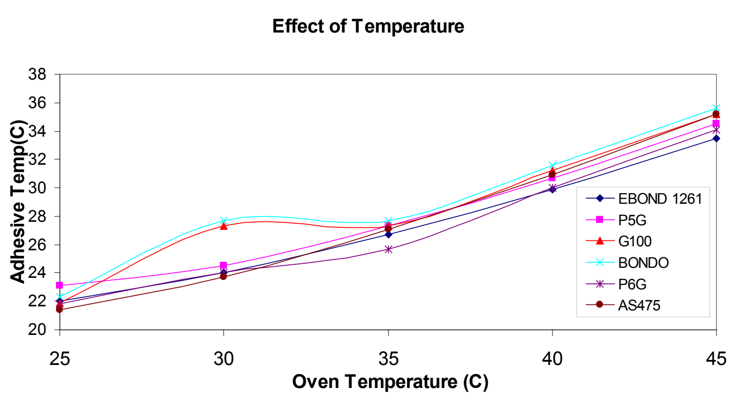

FIGURE 3-19.Heat Transfer Test Effect on Adhesive

Chapter IV

STATES SURVEY RESULTS

4.1 Introduction

This section reports on survey results of a detailed questionnaire that was sent to state highway agencies in the United States soliciting their experience with the installation and performance of piezoelectric sensors used for axle classification. The questionnaire was designed with the aim of determining devices, materials, and installation practices that may affect performance and durability of piezoelectric axle sensors. A number of questions were also aimed at determining the types of failure that are observed throughout the U.S. so that a better laboratory and field evaluation could be set up in the ongoing evaluation of piezo sensors at the FAMU-FSU College of Engineering. Appendix A shows the questionnaire while Appendix B shows the state DOT officials that were contacted.

4.2 Types of Sensors Used

The Transportation Statistics Office of the Florida Department of Transportation has approved two types of sensors for use at permanent and temporary traffic monitoring sites. These are: Roadtrax BL sensor manufactured by Measurements Specialties Inc. (MSI) and Vibracoax (a.k.a. Thermocoax) sensor manufactured by Phillips Electronic Instruments Company. The full manufacturer's information and device specifications are shown in Appendix C. In addition, a literature search also revealed one more piezoelectric axle sensor existing in the market. This is the Traffic 2000 sensor manufactured by Traffic 2000 Limited based in United Kingdom. The specification of this sensor is also shown in Appendix C. The survey questionnaire asked if the state is using any of these sensors and if they were aware of any other piezoelectric sensors in the market beyond the three mentioned above. The survey results on the type of sensors used by the states are shown in Table 4-1 below. A full list of States with type of sensors they use is shown in Appendix D.

TABLE 4-1. Types of sensors used by states

Type of Sensor	Number of States Using the Sensor
BL sensor	33
Thermocoax sensor	29
Traffic 2000 sensor	0

The results in Table 1 shows that both BL and Thermocoax sensors are almost equally used around the country. Further, Traffic 2000 sensor was not reported as being used in any state and virtually no state uses any sensor other than BL and Thermocoax. It should be noted that the survey covered only state departments of transportation; therefore, there are other jurisdictions such as cities, counties, and toll road agencies that were not surveyed. In addition, even though some states indicated that they use sensors other than those enumerated in Table 4, it is suspected that these are not piezoelectric sensors, or that they are a variation of BL and Thermocoax.

4.3 Types of Adhesive Material Used

The survey results shown in Table 4-2 reveals that that G100 has been the most used adhesive. The results also show that AS475 and P5G are approximately equally used followed by PU200. The results show that 7084 grout is the least used.

TABLE 4-2. Types of adhesives used by states

Type of Adhesive	Number of States Using the Adhesive
G100	26
7084	11
P5G	21
AS475	20
PU200	18

A preliminary literature review showed that there are numerous manufactures of adhesives; therefore, in addition to the above adhesives, the survey questionnaire also asked which other types of adhesives were in use. The results of the survey on this question are summarizes in Table 4-3.

TABLE 4-3. Other adhesives reported being used

Type of Adhesive	Manufacturer/Distributor	States Using the Adhesive
P-606	Bondo	Nebraska
Degugga Degadur VP 4609	International Road Dynamics (IRD)	Connecticut
Dural 331	Tamms Industries	Michigan
Aggrikote	Streeter Amet/ Peek	Wisconsin
Hermitite	Stagg	Iowa

4.4 Field Installation Practices

Of importance to the performance and durability of the sensor installations is the quality control during the installation. Survey questions were formulated to solicit state's practices in installing piezoelectric axle sensors in various roadway and environmental conditions. The following sections summarize the results of states' sensor installation practices ranging from groove cutting to opening the site to traffic.

4.5 Groove Cutting

Most states (39) reported that they use a water-lubricated cutting saw to cut a groove in the pavement. Out of these, eight states reported using both dry and water lubricated cutting saws. Only five states reported practicing dry-cut without any form of lubrication. One state did not indicate whether it uses lubricated or dry cutting saw. Almost all states reported that after cutting the groove it is cleaned free of water and dirt using a pressurized hot-air blower.

4.6 Adhesive Mixing & Pouring

Practically all states that reported using axle sensors indicated that the mixing of the two-part adhesive (i.e., resin and hardener) is done manually using a hand drill. No state reported using any machine to mix and pour the adhesive at a uniform rate. The State of Wisconsin reported that they have developed a simple plywood device that is used to insure that the sensor is placed at a consistent depth along the length of the grove (Figure 4-1). The device is used to press the sensor into the grove to a predetermined depth.

FIGURE 4-1. The Wisconsin Device for Maintaining a Uniform Installation Depth

4.7 Curing of Adhesive

No concrete data was obtained on this question, but a telephone conversation with one state representative indicated that the adhesive is generally allowed to cure from 30 to 60 minutes before opening the road to traffic. A number of states reported using heating devices to speed up the curing during cold installation. A few states reported foregoing installation altogether during the winter to avoid curing problems.

4.8 Quality Control

To ensure quality control during the installation, eighteen (18) states reported that they have either adhesive or automatic data recorder (ADR) manufacturer's representative present during the installation. However, some of these states indicated that they only have these representatives during the first installation. In addition, thirty-six (36) states indicated that they have qualified DOT personnel present during the installation to ensure quality.

The questionnaire further solicited input on the nature of the crew that installs piezos in the states. The survey wanted to know whether the state departments of transportation rely on specialized crews that travel throughout the state to install piezos. Thirty (30) states reported that they have specialized crews for sensor installation while fifteen (15) states do not have specialized crews.

4.9 Performance Observations

In order to institute a well-designed laboratory and field evaluation plan, the states were asked to narrate their experience with the performance of the piezoelectric sensors beyond the installation phase. The questions were devised to determine sensor performance, adhesive performance, and types of failure that were occurring. The following is the summary of the findings.

4.10 Sensor Performance

One of the major performance measures of the sensor is its durability. The respondents were asked to use their best judgment in answering how long do the sensors last before failure. For lack of precise definition of failure, it is assumed that the reported results relate to failure to get reliable output from the sensors rather than structural failure of the installation. The results of the reporting states were averaged and show that:

(a) The sensors last 4.49 years in flexible pavements, and
(b) The sensors last 5.18 years in rigid pavements.

4.11 Adhesive Performance

Sixteen (16) states reported that bonding between the pavement and the adhesive layer has been sustained over the life of the sensor while seven 7 states reported that the bonding has not been sustained. It was also pointed out by some states that bonding sustainability depended on the type of the pavement and the adhesive used. Michigan, for example, reported that bonding is sustainable for concrete pavement and not sustainable for asphalt. While there were variations in assessment of the performance of different adhesives, most states seem to be satisfied with the performance of ECM P5G. For example Oklahoma in particular reported that E-Bond G100 has poor performance characteristics in flexible pavement while ECM P5G had the best performance. One state, New Mexico, suggested that the primary reason for pavement-adhesive bond failure is the stiffness of the adhesive material used.

4.12 Types of Failure

There are two types of failures that were reported, i.e., failure involving sensor output and failure involving the structural integrity of the installation.

4.12.1 Signal output failure

It was reported that sensor signal output is affected by extreme heat and cold. The State of Maine reported that they have observed the BL sensor does not function well when the weather is really cold. While the State of Connecticut reported that the signal output is extremely temperature sensitive, particularly with Philips sensors, the State of Wisconsin reported that the lower temperature lowers the signal. The state of Wisconsin reported also that the output is highly affected by the snow.

4.12.2 Structural failure

Several modes of failures were reported including bond failure between the pavement and the adhesive, cracking at the bond joint, and failure due to the aging of the pavement and the adhesive used. Adhesive cracking due to water intrusion was reported especially by states that experience freezing during the winter. Some states reported that they have observed cracking and pavement failure in the vicinity of the piezo installation.

4.12.3 Other failures

Other types of failures commonly reported include splice failures, lightning strikes, lead-in cables being destroyed by moths and mice, and deterioration of the coaxial cable. It was noted that road maintenance crews sometimes inadvertently cut the coaxial cable when performing routine maintenance on roadways. Failure due to mishandling of sensors prior to installation was also reported. Accidents during construction were also reported to be among the causes of sensor failure. Georgia reported that improper depth cutting, loss of control of epoxy during installation and sensors not set to proper depth are among causes for sensor failures.

4.13 States Recommendations

The survey questionnaire solicited recommendations from States agencies on how the performance and durability of the piezoelectric axle sensor installations can be improved. The recommendations were geared towards pre-installation, installation, and post-installation practices that are likely to positively influence the performance of the sensors. The recommendations that were made are summarized in Table 4-4.

The survey results also indicated that no state has developed material testing procedures or wrote specifications for adhesive materials specifically for use in piezoelectric axle sensor installations. However, the respondents gave the recommendations shown in Table 4-5 on the question of which test they think is important in evaluating the performance of adhesives. The results in Table 4-5 show that the bonding between the pavement and the sealant and between the sealant and sensor as well as the water absorption characteristics of the sealant are very important in performance prediction of an adhesive material. Likewise, the respondents seem to think that electrical insulation property of an adhesive is not too relevant in long-term performance of a piezoelectric axle sensor installation.

TABLE 4-4. States recommendations on improving piezoelectric axle sensor performance

Pre-Installation Phase	**Shipping & Handling**	• Proper handling of adhesive cans • Proper storage of the adhesives prior to usage. Manufacturers instructions on storage of the adhesives should be carefully followed • Proper handling of the sensor to avoid excessive bending and scratching which may cause malfunctioning of the sensor
	Site Selection	• Level, straight and sound pavement with no cracks • Sensors should not be installed in thin overlays • The installation should be located where there is stable traffic flow
Installation Phase	**Groove Cutting / Sensor Placement**	• Must be power-washed and dried at least twice • The groove must be as small as possible and according to manufacturer recommendation • Depth of the groove in asphalt should not be less than two inches • A gauge should be used to control the depth and width of the groove • Sand papering of the sensor in order to increase the bonding between the sensor and grout interface • Wearing of gloves to keep sensor free from perspiration/hand prints
	Mixing / Pouring	• Adhesive must be viscous enough • Adhesive must be poured immediately after mixing • The materials on the wall of the container should not be scratched and poured since it may not be sufficiently mixed • The container should not be reused since it may contain some material on the walls that may react and cause inconsistency in the mixture
Installation Phase	**Curing**	• Cure time must be sufficient • A tool with a sharp point should be used to check if the grout is cured properly before opening the road to traffic
Post-Installation Phase		• Dropping a falling weight in order to check the uniformity of the sensor output throughout the sensor length • Excessive grout may be removed by grinding

The survey results also indicated that no state has developed material testing procedures or wrote specifications for adhesive materials specifically for use in piezoelectric axle sensor installations. However, the respondents gave the recommendations shown in Table 4-5 on the question of which test they think is important in evaluating the performance of adhesives. The results in Table 4-5 show that the bonding between the pavement and the sealant and between the sealant and sensor as well as the water absorption characteristics of the sealant are very important in performance prediction of an adhesive material. Likewise, the respondents seem to think that electrical insulation property of an adhesive is not too relevant in long-term performance of a piezoelectric axle sensor installation.

TABLE 4-5. Recommendations on laboratory material testing

Laboratory Test	**Average States Score***
Hardness	3.7
Shrinkage	3.9
Water Absorption	4.1
Bonding/Adhesive Strength with Sensor	4.2
Bonding/Adhesive Strength with Pavement	4.7
Fatigue Strength	3.9
Aging Due to Environment & Cyclic Loading	3.6
Electrical Insulation Properties	3.1
Thermal Conductivity and Temperature Effect	3.7

*1—Least Important and 5—Very Important

Chapter V

BETTER INSTALLATION PRACTICES

5.1 Overview

The performance and durability of piezoelectric axle sensor installations depends on numerous factors among which quality control during installation plays a major role. Field experience indicates that improper installation of sensors can lead to errors in signal output and can decrease the durability of sensors. This section is a synthesis of better installation practices that is aimed at improving the performance and longevity of piezoelectric axle sensor installations. The section is a compilation of information gained from interviews with experts in different states and observation of field installation of piezos in the State of Florida. The manual explains practices that have been found to work well in previous installations around the country. It covers all aspects of installation including pre-installation and post-installation practices.

5.2 Objectives

The objective of this manual is to synthesize best installation practices that can be used in Florida to increase the durability and improve performance of piezoelectric axle sensor installations at permanent and temporary traffic monitoring sites. The manual is intended for installation crews that regularly install sensors on Florida highways. The manual offers guidelines and suggestions on how to achieve effective installation of piezos through better handling and installation quality control. The practices are primarily aimed at installation of piezos in flexible pavements but can also be used when installing piezos in portland cement concrete pavements.

5.3 Scope

The manual covers pre-installation issues including material handling and site selection. Next, the manual addresses on-site installation issues including groove cutting, mixing, and pouring of adhesive into the groove. Finally, the manual addresses post-installation issues that include curing time prior to opening to traffic, signal testing and other issues. The manual is predicated on the fact that field installation crew already have experience in piezo installation and what is suggested in this manual are ways to make installations better and durable.

5.4 Pre-Installation Considerations

5.4.1 Site selection

The selection of the site for piezo installation is of paramount importance since field experience indicates that a site with poor characteristics would contribute to premature failure and lack of uniform and sustained signal output from the piezo. The most important factors to consider in site selection include pavement characteristics, drainage characteristics, and site topography.

5.4.2 Pavement characteristics

Generally, climate, age, and traffic combine to cause deterioration in asphalt pavements. These deteriorations manifest in the form of alligator (or fatigue) cracking, longitudinal cracking, transverse cracking, depression, and rutting. Alligator or fatigue cracking is a series of interconnecting cracks caused by fatigue failure of asphalt concrete surface under repeated traffic loading. Longitudinal cracks are parallel to the pavement's surface and may be caused by a poorly constructed paving lane joint, shrinkage of the asphalt concrete surface, or a reflective crack caused by cracks beneath the surface course. Transverse cracking extend across the pavement centerline or direction of the laydown and may be caused by similar factors that cause longitudinal cracks. Depressions are localized pavement surface areas having elevations slightly lower than those of the surrounding pavement. Depressions are caused by settlement of the foundation soil or can be "built in" during construction. Rutting is a surface depression in the wheel path and is caused by permanent deformations in any of the pavement layers or subgrade due to traffic loads.

It is important that a sensor not be installed in any area of the pavement surface exhibiting any of the above distresses. The pavement in these areas is likely to accumulate water which could lead to further deterioration of the pavement and lack of proper and uniform signal output across the whole length of the sensor.

5.4.3 Drainage characteristics

Pavements are generally designed to drain longitudinally through provision of minimum grade, generally ½%, and laterally through provision of cross slopes, generally 1.5% to 3%. But due to various factors—such as construction deficiencies, maintenance shortfalls, and geometric deficiencies—there are areas on the highway that do not allow rapid drainage of water from the pavement surface. Installation of a sensor in these areas would increase the likelihood of water entering the bottom layers thus causing localized failures within the sensor vicinity. These areas should thus be avoided.

5.4.4 Site topography

Piezo sensors installed for the purposes of capturing traffic data in highway sections should be installed outside the area of influence of intersections. Intersection areas are characterized by frequent stops, acceleration, and deceleration maneuvers that are likely to skew the data. In addition, in intersection areas vehicles are likely to spill oil on the sensor which might cause deterioration if the adhesive is not chemically resistant.

5.4.5 Traffic characteristics

Sensors should be installed where there is free flow traffic. Locations where traffic may be braking, queuing or accelerating should be avoided. This may occur at bends, sloping areas junctions, and building access, intersections, entrance and side street access. Areas that are subject to excessive lane changes should also be avoided. Lane changes may cause errors in recording which may result in wrong sensor outputs.

5.5 Material Selection

Both the sensor and adhesive material must be selected carefully. Currently, there are only two sensor types that have been approved by FDOT, that is BL sensor by MSI and Thermocoax by Phillips. A survey of states on the use of these sensors indicated that they are both equally used. Without a detailed scientific evaluation of the performance of these two sensors, only non-technical factors such as cost, warranty, customer support, ease of handling, etc., need to be considered in choosing which type of sensor to install.

The selection of adhesive would depend on whether the installation is on asphalt concrete pavement or portland cement concrete pavement. Generally, softer adhesives are suitable for asphalt concrete pavements while harder adhesives perform well with portland cement concrete pavements. A detailed study of all adhesives approved by FDOT Planning Office is currently underway to develop test procedures and material specifications for future use in selecting adhesives. A recent preliminary report submitted to FDOT suggested that acrylic-based adhesives should be used with increasing frequency in the installation of piezos in flexible pavements. There are only two acrylics-based adhesives approved by FDOT—that is, ECM P5G and IRS AS475.

5.6 Material Handling

It is important that both the sensor and adhesive should be shipped, handled, and stored properly according to manufacturer's recommendations. Piezoelectric strip sensors are very fragile and should not be bent or scratched. Minor bending or scratching may cause malfunctioning of the sensor. Adhesives are made of polymers that are reactive. If the container is mishandled—causing deformation—change in volume may produce undesirable reaction that may change polymer properties. Inspecting the sensor and the adhesive prior to installation can reveal deformities or flaws that need to be corrected before they are buried into the ground.

5.7 Weather Condition

A good installation can be achieved in a dry clear day compared to installation undertaken during inclement weather conditions. It is therefore important to schedule installation on clear days to avoid water intrusion in the groove. Considering that the groove has to be dry and clean prior to placing the sensor and pouring adhesive, it is important that there should not be rain or moisture present during this crucial phase of the installation.

5.8 Equipment and Crew

Installation of piezoelectric sensors requires specialized equipment. The use of a trained crew with experience and dedication to the job will ensure a quality that will result in a longer lasting installation. Field observations of installations on a number of sites in Florida indicated that unless there is proper supervision at the site, the contractor or FDOT should ensure that the crew is reliable and would not cut corners on any phase of the installation process.

5.9 Installation Considerations

5.9.1 Site inspection

Prior to installation, the crew should inspect the site to make sure that it is the proper location for installation. If the installation is a replacement of failed sensors, the crew needs to determine visually why the sensors failed. This should be done in order to eliminate poor site characteristics as a contributing factor to the failure. The crew should also inspect the integrity of the connections to the cabinet, including lead-in cables, pull boxes, and the automatic data recorder (ADR) cabinet. The crew should decide where the new sensors should be installed. It is inadvisable to install new sensors by cutting grooves in the same place as failed sensors. This will introduce weaknesses in the groove and will not result in a good bonding strength.

5.9.2 Groove cutting

The groove should be cut in exactly the same size as suggested by the sensor manufacturer, generally ¾ inch x ¾ inch x 6 feet. A larger groove size than specified will cause the chairs not to stick to the ground and will likely require more adhesive to fill. It is important that the groove be cut in a single sawing operation, with no chipping or jackhammering to minimize damage to the pavement. Water lubricated pavement saw-cutting is preferable to dry-cutting. The water cools the blade, makes a smooth cut, and controls dust. It is worthy mentioning that dry cutting forces particles into walls of the grove that are very difficult to thoroughly clean. This residue diminishes the adhesion of the adhesive to the road, potentially allowing for the premature failure of the sensor. The cutting should be controlled and monitored carefully to ensure the groove is in form of a straight line.

All weak sections and loose particles and unsound pavement material must be chipped out followed by brushing and/or vacuuming. All paints, oil, grease and other contaminants should be removed using solvents and/or detergents as required to ensure the absolute cleanliness of the surface.

After cutting, the three groove surfaces should be prepared carefully; first, by water-blasting to remove dirt and dust, and secondly by hot-air drying to totally expel moisture from the groove surfaces. Caution should be taken not to spray loose material into active traffic lanes and personnel should be appropriately attired. Good adhesion between the pavement and the grout can only be obtained when the surface of a substrate is prepared correctly. Dust, laitance, grease, or any contaminant that would adversely affect the bond should be removed. Maximum bonding strength can only be assured when the surfaces to be bonded are totally clean and dry.

5.9.3 Preparing and placing the sensor into the groove

The BL sensor should be cleaned prior to fixing the chairs onto it. The cleaning of the surface helps to ensure that the sensor if free of debris to promote bonding strength. Studies show that polymers bond well with brass if they are cleaned with solvents before abrading. The cleaning solvent depends on the type of adhesive to be used. For acrylic-based adhesives the recommended solvent is methanol and for epoxies and polyurethanes the recommended solvent is acetone. The cleaning procedure involves wiping the sensor with the solvent, abrading with emery cloth, and then wiping again to ensure removal of all debris. The abrading also helps to roughen the surface to increase bonding strength.

During removal of the sensor from the packaging, ensure that you don't unduly bend the sensor. If the sensor is excessively bent, irreversible damage may occur. Do not lift from the center of the sensor. Instead the sensor should be lifted with uniform support along the length of the sensor.

The piezo can be bent slightly, if necessary, to follow the contour of the road surface. Levelling plates may be attached to the top of the piezo with wire in order to control the depth of the piezo below the top of the grove. This will ensure that the sensor follows the contour of the pavement the result of which is uniform reading along the length of the sensor. The sensor should be laid in the groove using the chairs as the support laterally. The chairs should then be spaced at an interval not more than 6 inches along the length of the sensor. Longer spacing of the chairs can cause sagging of the sensor in some areas. The last 2 inches of the sensor on each side must be bent down at an angle of about 15^0 in order to enhance anchorage at the ends.

5.10 Adhesive Mixing and Pouring

The adhesive should be prepared strictly according to manufacturer's instructions. Adhesives are normally supplied in two parts—resin and hardener. Most manufacturers require the resin to be mixed thoroughly prior to adding the hardener. The manufacturers supply the resin and the hardener in cans already pre-measured so that there is no need to calculate the mix ratio. Proper mixing is critical both before and after the addition of the activator. The resin and hardener should be thoroughly mixed using a hand drill for a pre-specified period of time as indicated in the product data sheet. Most crew prefers mixing the material in the can that contains the resin. Care should be taken that the can is well-rounded and does not contain kinks that can affect the mixing efficacy. Mixing should be done at low speed to ensure air bubbles are not introduced into the grout.

The materials should be mixed thoroughly taking care that the walls and the bottom of the mixing container are scraped to assure complete mixing. Care should be taken when mixing the grout to minimize the amount of entrapped air in the material. Lifting the missing paddle out of the grout may cause air entrapping in the grout. The grout should be poured immediately after completing the mixing operation. The grout should not be allowed to cure in the container.

The adhesive should be poured into the groove expeditiously after mixing within the manufacturer's suggested working time. The pouring should be done slowly and carefully making sure that the adhesive flows around the sensor and the chairs totally encapsulating them. Care should be taken to avoid air voids being created underneath the sensor. The adhesive should be filled such that it is flush or slightly above the road surface. If duct tape was used on groove sides, it should be removed as soon as the adhesive starts to harden, leaving a clean installation.

Once the sensor is installed and the grout is initially cured, it is recommended that any excessive grout be ground off, using an angle grinder. The best installation has the grout flush with the road surface to minimize any chances of the tires bridging over the sensor.

5.11 Post-Installation Considerations

5.11.1 Curing

The adhesive poured into the groove should be allowed to gain sufficient strength prior opening the site to traffic. The length of the curing time can range from 45 minutes to two hours but should be according to the manufacturer's recommendation. During the curing time, the crew generally works on pulling lead in cables through pull boxes and the ADR cabinet. The crew should resist the temptation to open the road to traffic early since premature axle loading of the adhesive can cause permanent damage by inducing internal stresses into the adhesive thus preventing full bonding and crosslinking.

5.11.2 Testing

A falling weight deflectometer (FWD) test should be used to check signal output along the sensor. The falling weight should be hammered at different points along the sensor installation to check for the uniformity of the output along the sensor.

5.11.3 Reporting

A comprehensive form should be used to record necessary information during installation. Several information including the type of grout used, type of sensor, weather condition, type of failure observed and so forth may help to modify the installation practice in the future. All unusual events must be documented for future reference.

Chapter VI

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

The materials studied can be categorized in three main groups – epoxies, polyurethanes and acrylics. Different sources that were used to examine each type of bonding materials i.e., literature review, state experience survey and laboratory testing suggest that there are distinctive properties associated with each material. The following discussion is a synthesis of information found from various sources and would build a basis for the recommendations about to be made.

Epoxies

The laboratory results shows that epoxies are associated with hardness behavior, high compressive strength, with high modulus of elasticity. No significant difference was observed between epoxies and other types of materials. The epoxies were also found to have relatively higher peel strength with an exception of Bondo 7084. The epoxies also resulted with higher peel strength. However laboratory results suggested little flexibility of epoxy materials with exception on E-Bond 1261.

The state survey respondents commented on some epoxies. The respondent from the State of Connecticut reported that G100 performed well in concrete pavement installations while it developed cracks when sensors were installed in asphalt pavements. The State of Utah reported that it had used G100 in the past but it failed in the first summer after installation. The State of West Virginia also reported that at numerous sites installed with G100 cracks were observed. The State of Nebraska reported that 7084 adhesive was very stiff during installation but had minimum cupping and weather effects. The State of Kentucky reported that 7084 adhesive did not have good long term bonding characteristics. E-Bond 1261 was not in use around the country at the time of this study, therefore there was no information about the product from states' survey.

Polyurethanes

As with epoxies, the laboratory results showed that polyurethanes are associated with hardness behavior but with lower compression strength and modulus of elasticity. The results further suggest that polyurethanes have the lowest peel strength among the rest of the materials. PU200 is the only polyurethane material that was reported to be used by some states. The respondent from the State of Virginia said that PU200 has not performed well in the state and he suspected that the material could be suffering from long-term creep and stress relaxation problems. In addition, according to one FDOT contractor, eighteen sites in Ohio installed with PU 200 have failed. The contractor suspects that part of the problem with PU200 is excessive shrinkage, which affects bonding between the sensor and the adhesive.

Acrylics

Contrary to epoxies and polyurethanes, laboratory test results suggested that acrylics are softer than epoxies and polyurethanes. The laboratory results also indicated that acrylics have lower compressive strength, lower modulus of elasticity and moderate strain hence reasonably more flexible than epoxies and polyurethanes, with an exception of E-Bond 1261. While P5G and P6G resulted in relatively lower peel strength, AS475 resulted in higher peel strength than some polyurethanes and epoxies.

Several states reported on performance of acrylics (P5G and AS475). The State of Kentucky reported that P5G had good long term bonding characteristics while Colorado surmised that since switching to P5G from other adhesives, the failure rate of piezo installations has been greatly reduced. The State of Montana reported that they have been pleased with the performance of P5G since most of the failures have been in cabling, sensor itself, and pavement, but generally not the adhesive. However, Montana also reported that they noticed that when P5G is installed in pavements with thin overlays it generally tends to fail prematurely. The State of Washington reported that using AS475 has greatly reduced their piezo installations failure rate. Likewise, the State of Utah reported that the field crew prefers AS475 over PU200 since it mixes and pours well, as well as it cures quicker than PU200. The study by Euber *et al*. (1994) also found that acrylic-based adhesives performed better than epoxies in most cases during the field trials.

6.2. Recommendations

Based on the literature review, state survey and laboratory test results it is recommended that the Florida Department of Transportation should use acrylic-based adhesives with increasing frequency in the installation of piezoelectric axle sensors in asphalt concrete pavements. Though there are only two acrylic-based adhesives currently approved by FDOT, i.e., IRD AS475 and ECM P5G, it is recommended that P6G, the modified product of P6G be included in the Florida Department of Transportation approved list of adhesives. It is also recommended that a monitored field test be conducted on E-Bond 1261, the only epoxy-based material that had a number of properties that may be suitable for installation of piezoelectric axle sensors in asphalt concrete pavements.

Chapter VII

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APPENDICES

APPENDIX A

A SURVEY OF STATE DOT'S EXPERIENCE WITH POLYMER BINDERS FOR USE WITH PIEZOELECTRIC AXLE SENSORS

1. Does your agency use the following piezoelectric sensors for axle classification?

(a)	Roadtrax BL Sensor by Measurement Specialties, Inc.	Yes	No
(b)	Vibracoax by Phillips Electronic Instruments Co. (Thermocoax)	Yes	No
(c)	Traffic 2000 by Traffic 2000 Limited (United Kingdom)	Yes	No

Please mention below other sensor types for your agency is using or you are aware to be currently available in the market:

Sensor type	Manufacturer
(d) ______________________	____________________________________
(e) ______________________	____________________________________
(f) ______________________	____________________________________
(g) ______________________	____________________________________

2. Does your agency use the following polymers for encapsulating or holding the sensor into the pavement?

Epoxy binders

(a)	G-100 by E-Bond Epoxies Inc.	Yes	No
(b)	Bondo 7084 by Dynatron/Bondo Corporation	Yes	No

Acrylic Binders

(c)	ECM P5G by Electric Control Measurement	Yes	No
(d)	AS475 by International Road Dynamics	Yes	No

Polyurethane Binders

(e)	PU 200 by Global Resins Limited	Yes	No

Please mention below other adhesive materials your agency is using or have used in the past:

Polymer Binder	Manufacturer/Distributor
(f) ______________________	____________________________________
(g) ______________________	____________________________________
(h) ______________________	____________________________________
(i) ______________________	____________________________________

3. Which of the polymer binders mentioned above is used with flexible or rigid pavements?

Binder Name	Used with Flexible Pavements	Rigid Pavements
(a) ______________	__________________	________________
(b) ______________	__________________	________________
(c) ______________	__________________	________________
(d) ______________	__________________	________________
(e) ______________	__________________	________________
(f) ______________	__________________	________________

4. The following questions relate to field installation procedures.

(a) Do you use dry cutting saws or water lubricated cutting saws? __________________

(b) Is mixing of two-part adhesives done manually or by a machine? ________________

(c) Is pouring of the adhesive done manually or by a metering machine? _____________

(d) In installing a bare sensor (e.g., BL sensor), how is the binder encapsulated around it? ____

(e) Do you use heating devices to speed up curing in cold temperatures? ____________

(f) How is the quality of the installation assured or verified? ______________________
____

(g) Do you have a representative from the sealant or ADR manufacturer present during the installation? ____

(h) Do you have a DOT personnel present during the installation to ensure quality? ___

(i) Do you have a specialized crew installing piezos throughout the whole state? _____

5. On the average how long do your sensor installation last

(a) in flexible pavements?_________________

(b) in rigid pavements?___________________

6. The following questions relate to the performance of the sensors after the installation.

Sensor signal output

(a) Has the sensor signal output been predictable and repeatable over the life of the sensor? ____

(b) Has the sensor signal output been uniform over the length of the sensor and over the life of the sensor? ____

(c) Has the sensor signal output been relatively unaffected by the change in temperature? ____

Polymer binder performance

(a) Has the bonding between the pavement and polymer been sustained over the life of the sensor? ______________________________

(b) Has the bonding between the polymer and the sensor been sustained over the life of the sensor? ______________________________

(c) Has the pavement structure in the vicinity of the sensor remained strong over the life of the sensor? ______________________________

7. What types and modes of failures do you frequently observe in piezoelectric axle sensor installations?

(a) ______________________________

(b) ______________________________

(c) ______________________________

(d) ______________________________

(e) ______________________________

(f) ______________________________

8. The following questions relate to causes of failures identified above:

(a) How significant is the failure due to the bonding material being too stiff or soft at the time of the installation? ______________________________

(b) How significant is the failure due to improper installation e.g. air pockets, lack of total encapsulation? ______________________________

(c) How significant is the fatigue failure due to large and/or excessive axle loads? ______________________________

(d) How significant is the failure due to lightening? ______________________________

(e) How significant is the failure due to incompatibility between ADR and the sensor? ______________________________

(f) How significant is the failure due to the loss of electrical insulation between the ground and the sensor? ______________________________

(g) How significant is the failure due to ingress of water reaching the sensor through cracks? ______________________________

(h) How significant is the failure due to loss of structural stability of the pavement surrounding the sensor? ______________________________

9. List other causes of failures that you have observed

(a) ______________________________

(b) ______________________________

(c) ______________________________

(d) ____

(e) ____
_

(f) ____

10. Do you have any suggestions on how the following can be changed to improve performance?

(a) Sensor Design ____

(b) Groove or Slot size ____

(c) Installation Procedures ____

(d) Grout/Sealant Material Characteristics _________________________________

(e) Site Selection ____

11. Has your state developed test procedures for polymer binders specifically for use in piezoelectric sensor installation? _______________________________________

12. Has your state developed material specifications for polymer binders specifically for use in piezoelectric sensor installation? _______________________________________

13. On a scale of 1 to 5 (1 - Least Important, 5 - Very Important) give your views on which laboratory material properties tests are likely to better predict the long term performance of sensor-binder-pavement combination?

Laboratory Test	**Your Score**
Hardness	
Shrinkage	
Water Absorption	
Bonding/Adhesive Strength with Sensor	
Bonding/Adhesive Strength with Pavement	
Fatigue Strength	
Aging Due to Environment & Cyclic Loading	
Electrical Insulation Properties	
Thermal Conductivity and Temperature Effect	

ANY OTHER COMMENTS

APPENDIX B

LIST OF RESPONDENTS

First Name	Last Name	JobTitle	Company	City	State	WorkPhone	Fax	Email
Howard	Helkenn	Highway Data Manager	Alaska Department of Transporation and Public Facilities	Anchorage	AK	907-269-0876	907-269-0878	howard_helkenn@dot.state.ak.us
Charles	Turney	Civil Engineer Administrator	Alabama Department of Transportation	Montgomery	AL	334-242-6393		turneyc@dot.state.al.us
Alan	Meadors	Staff Research Engineer	Arkansas Highway and Transportation Department	Little Rock	AR	501-569-2380	501-569-2070	alan.meadors@ahtd.state.ar.us
Bob	Pike	Data Development and Analysis Group	Department of Transportation and Public Facilities	Phoenix	AZ	602-712-8228		
Joe	Avis	Research Manager	California Department of Transportation	Sacramento	CA	916-654-3072		joe.avis@dot.ca.gov
Robert	Tenney	Head of Traffic Analysis Unit	Colorado Department of Transportation	Denver	CO	303-757-9489	303-757-9974	robert.tenney@dot.state.co.us
Edward	Majcherek	Electrical Design Engineer	Connecticut Department of Transportation	Newington	CT	860-594-2795		edward.majcherek@po.state.ct.us
Robert	Hutson	Traffic Systems Operations Manager	Delaware Department of Transportation	Dover	DE	302-739-4366	302-739-6792	rhutson@mail.dot.state.de.us
Ron	Harris	Transportation Data Collection Branch Chief	Georgia Department of Transportation	Shamble	GA	770-986-1364	770-986-1056	ron.harris@dot.state.ga.us
Alan	Leung	Planning Survey Engineer	Hawaii Department of Transportation	Honolulu	HI	808-587-1838	808-587-1787	daleung@juno.com
Phillip	Meraz	Statistics Research Analyst	Iowa Department of Transportation	Aimes	IA	515-239-1526	515-239-1828	phillip.meraz@dot.state.ia.us
Scott	Fugit	WIM Supervisor	Idaho Department of Transportation	Boise	ID	208-334-8207		
Rob	Robinson	Data Management Unit Chief	Illinois Department of Transportation	Springfield	IL	217-785-2353	217-524-6251	robinsonre@nt.dot.state.il.us
Lowell	Basey	Senior Traffic Data Collection Technician	Division of Roadway Management	Indianapollis	IN	317-591-5262	317-591-5230	
Bill	Hughes	Weigh In Motion Engineer	Kansas Department of Transportation	Topeka	KS	785-296-3841	785-296-8168	bhughes@ksdot.org
Dan	Inabnitt	Equipment Management Team Leader	Kentucky Transportation Cabinet	Frankfurt	KY	502-564-7183	502-564-2865	Dan.inabnitt@mail.state.ky.us
Robert	Smith	Traffic & Planning Supervisor	Lousiana Department of Transportation	Baton Rouge	LA	225-274-4110	225-274-4160	jblack@dotdmail.dotd.state.la.us
Stephen	Greene	Transportation	Massachussets Highway	Boston	MA	617-973-7327	617-973-8058	Stephen.Greene@mhd.state.ma.us

First Name	Last Name	JobTitle	Company	City	State	WorkPhone	Fax	Email
		Programmer	Department					
Barry	Balzanna	Traffic Monitoring Systems	Maryland Department of Transporation	Baltimore	MD	410-545-5509	410-209-5033	bbalzanna@sha.state.md.us
Debbie	Morgan	Tech IV	Maine Department of Transportation	Augusta	ME	207-287-2035	207-287-3725	deborah.morgan@state.me.us
Robert	Brenner	Senior Equipment Technician	Bureau of Transportation Planning	Lansing	MI	517-322-1673	517-373-9255	brennerr@mdot.state.mi.us
George	Cepress	Forecasting Engineer	Minnesota Department of Transportation	St. Paul	MN	651-296-0217		george.cepress@dot.state.mn.us
Allan	Heckman	Supervisor of Analysis and Reports	Missouri Department of Transportation	Jefferson City	MO	573-751-2842		heckma@mail.modot.state.mo.us
Carolyn	Thornton	Traffic Analyst Supervisor	Mississippi Department of Transportation	Jackson	MS	601-359-7685	601-359-7652	cthornton@mdot.state.ms.us
Dan	Bisom	Data Collection Supervisor	Montana Department of Transportation	Helena	MT	406-444-6122	406-444-7671	dbisom@state.mt.us
David	Page	Traffic Monitoring Supervisor	North Carolina Department of Transportation	Raleigh	NC	919-733-4796		page@dot.state.nc.us
Robert	Speckmann	Project Manager	Planning & Programming Division	Bismarck	ND	701-328-4401		bspeckma@state.nd.us
Terry	Guy	Supervisor of Traffic Count Shop	Nebraska Department of Roads	Lincoln	NE	402-479-4509	402-479-4687	tguy@dor.state.ne.us
Suramanian	Sharma	Traffic Research Engineer	New Hampshire Department of Transportation	Concord	NH	603-271-1625	603-271-8093	bureau46@dot.state.nh.us
Louis	Whitley	Chief, Traffic & Technology Section	New Jersey Department of Transportation	Trenton	NJ	609-530-3501	609-530-3514	louis.whitley@dot.state.nj.us
Billy	Larranaga	Planning Supervisor	New Mexico State Highway and Transportation Deparment	Santa Fe	NM	505-827-5380	505-989-4983	billy.larranaga@nmshtd.state.nm.us
Charles	Cerocky	Transportation Analyst III	Nevada Department of Transportation	Carson City	NV	775-888-7442	775-888-7267	ccerocky@dot.state.nv.us
Michael	Fay		Highway Data Services Bureau	Albany	NY	518-457-7203		mfay@gw.dot.state.ny.us
Dave	Gardner	Traffic Monitoring Section Manager	Ohio Department of Transportation	Columbus	OH	614-466-3727		dgardner@state.dot.oh.us
Daryl	Johnson	Traffic Analyst Supervisor	Oklahoma Department of Transportation	Oklahoma City	OK	405-521-2575	405-521-6917	djohnson@odot.org
David	Fifer	ITS Specialist	Motor Carrier Transportation Division	Salem	OR	503-378-6054		david.a.fifer@odot.state.or.us
Dennis	Starr	Transportation Planning Specialist Supervisor	Bureau of Planning and Research	Harrisburgh	PA	717-787-4574	717-787-6376	dstarr@dot.state.pa.us
Joseph	Bucci	Chief Civil Engineer	Traffic & Safety Management	Providence	RI	401-222-2694	401-222-2207	jbucci@dot.state.ri.us
Joe	Boozer	Head of Traffic Count	South Carolina Department of	Columbia	SC	803-737-1118	803-737-0006	

First Name	Last Name	JobTitle	Company	City	State	WorkPhone	Fax	Email
		Section	Transportation					
Kenny	Marks	Engineering Supervisor	South Dakota Department of Transportation	Pierre	SD	605-773-3336		
Ray	Barton	Traffic Survey Supervisor	Tennessee Department of Transportation	Nashville	TN	615-350-4570		rbarton@mail.state.tn.us
Jeff	Reding	Field Systems Manager	Texas Department of Transportation	Austin	TX	512-465-7949		jreding@dot.state.tx.us
Gary	Kuhl	Engineer for Planning & Statistics	Utah Department of Transportation	Salt Lake City	UT	801-964-4552		
Michael	Pologruto	Technical Services Engineer	Vermont Department of Transportation	Montpelier	VT	802-828-3876	802-828-5742	mike.pologruto@state.vt.us
Rich	Rempfer		Washington Department of Transportation	Olympia	WA	360-570-2379	360-570-2400	remfer@wsdot.wa.gov
Steve	Wiswell	Shop Administrator	Division of Transportation Investment Management	Madison	WI	608-246-3266	608-246-5401	steven.wiswell@dot.state.wi.us
Jerry	Legg	Head of Traffic Analysis Section	Planning & Research Division	Charleston	WV	304-558-2864	304-558-3783	jllegg@dot.state.wv.us
Mike	Ashbrook		North Carolina Department of Transportation		NC	828-389-0320		mhashbrook@dot.state.nc.us

APPENDIX C

SENSOR SPECIFICATIONS

Material properties	SENSORY TYPE		
	VIBRACOAX	ROADTRAX BL	TRAFFIC 2000
Piezo-electric constant	1 V/bar	≥20 pC/N	15pC/N at 23^{o}C
Insulation Resistance (MΩ)	≥1000	≥500	>1000
Linear Capacitance (pF/m)	10,000		790
Temperature Range (^{o}C)	-20 to +70	-40 to 160	-40 to +70

SENSORS MANUFACTURERS' ADDRESSES

Sensor Type	Manufacturer's address
Roadtrax BL Traffic Sensors	Measurement Specialties, Inc. Sensor Products Division 950 Forge Avenue - Bldg B Norristown, PA 19403 (800) 745-8008 toll free Phone: (610) 650-1500 Fax (610) 650-1509 email: info@msiusa.com
Thermocoax Sensors	Philips Thermocoax 5110 McGinnis Ferry Road Alpharetta, GA 30202 Phone: (770) 751-4420 Fax: (770) 751-4450
Traffic 2000 Sensor	3 The Quadrant Richmond, Surrey TW9 1BP United Kingdom Phone: +44 (0)181 948 6736 Fax: +44 (0)181 332 0813 E-Mail: Sales@traffic-2000-co.uk

APPENDIX D

TYPES OF SENSORS USED BY STATES

State	Sensor Type		Adhesive Type				
	BL Sensor	Thermocoax Sensor	G100	7084	P5G	AS475	PU200
Alaska		☑	☑			☑	
Alabama	☑	☑			☑		
Arkansas	☑	☑	☑	☑	☑		
Arizona							
California		☑	☑			☑	
Colorado	☑			☑	☑		
Connecticut	☑	☑	☑	☑			☑
Delaware					☑		
Florida	☑					☑	
Georgia	☑	☑	☑	☑		☑	
Hawaii						☑	
Iowa	☑	☑			☑		☑
Idaho		☑			☑		
Illinois	☑	☑	☑		☑		☑
Indiana	☑					☑	☑
Kansas			☑		☑	☑	
Kentucky	☑	☑	☑		☑	☑	☑
Louisiana							
Massachusetts		☑		☑	☑		
Maryland	☑	☑	☑	☑			
Maine	☑			☑	☑		☑
Michigan	☑	☑	☑			☑	☑
Minnesota							
Missouri	☑	☑			☑		
Mississippi	☑	☑	☑				☑
Montana		☑			☑		
North Carolina	☑	☑	☑				☑
North Dakota		☑	☑		☑		☑
Nebraska	☑			☑		☑	☑
New Hampshire		☑			☑		
New Jersey	☑	☑	☑			☑	
New Mexico	☑						☑
Nevada		☑	☑		☑		
New York	☑		☑	☑		☑	
Ohio	☑	☑	☑				☑
Oklahoma	☑	☑	☑	☑	☑	☑	
Oregon	☑	☑				☑	
Pennsylvania	☑	☑	☑			☑	☑
Rhode Island					☑	☑	
South Carolina	☑		☑	☑			☑
South Dakota							
Tennessee	☑		☑		☑		
Texas	☑	☑	☑		☑		
Utah	☑		☑			☑	☑
Vermont	☑	☑				☑	
Virginia	☑					☑	
Washington	☑	☑	☑			☑	
Wisconsin	☑		☑				☑
West Virginia	☑	☑	☑		☑		☑
Total	**33**	**29**	**26**	**11**	**21**	**20**	**18**

APPENDIX E

SUMMARY OF ADHESIVE PROPERTIES

Property	Adhesive type				
	G100	7084	P5G	AS475	PU200
Hardness	85-88	80±5	50	65	85
Shrinkage	0%	0%	0%		
Water Absorption	0.03%	0%	0%	0.3%	
Adhesion Strength	2400 psi ASTM C-882 with Type II Center	2000±200 psi			
Fatigue Strength	7000 psi				
Compressive Strength	8000 psi		3583 psi	5000 psi	35 Mpa
Tensile Strength	5800 psi	2500±200 psi		450 psi	8 Mpa
Viscosity	Self leveling grout	500 poise	250 poise		270 poise
Pot life	17-25 min @ 77°F		10 min	10-40 min	10 min
Set time	100-200 min @ 77°F	45 min	11 min	<60 min	20 min
Gel Time	17 to 25 min at 77°F		13 min @ 25°C		10 min at 20°C