An Advanced Preformed Inductive Loop Sensor

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1 Introduction

Although inductive loops are still the most widely deployed, and possibly most reliable, transportation sensor system, over 25% of all inductive loops are malfunctioning at any given time. While this is down from figures of 50-60% in the early 1980's, it is still high enough to cause degradation of traffic control at signalized intersections, ramps and control systems. In the early 1980's, FHWA began to explore ways of reducing the malfunction rate of traffic sensors and particularly of loops. Several manuals were produced leading to the Traffic Detector Handbook [Traffic Detector Handbook, 2nd Edition, FHWA-IP-90-002, July 1990]. Premanufacturing traffic loops was one of the main concepts found during the research for the Traffic Detector Handbook.

These findings about different approaches to reducing loop failures led the United States Department of Transportation to solicit a small Business Innovative Research (SBIR) project in early 1996. This solicitation asked for new and innovative approaches to enabling loops to withstand the thermal and mechanical stresses of installation, changing environmental conditions, movement of pavement and abrasive chemical conditions.

ORINCON Corp. was awarded the SBIR Phase I contract in September 1996 to investigate preformed loop designs. Subsequently, an SBIR Phase II contract has been awarded to ORINCON to design, prototype and test preformed loop concepts developed during Phase I.

The purpose of the preformed loop project is to create a product that will create not only better lasting but also better performing preformed loops for traffic sensing. Phase I of the project created a preliminary design for a preformed product that would be competitive in price and superior in performance to non preformed loops.

Key requirements of the project are to make the design compatible with adverse installation conditions including possible high temperature conditions of hot asphalt or narrow cross section saw cuts. Ruggedness is required as the loop may be driven over by construction vehicles prior to resurfacing operations or handled badly by unfamiliar technicians. Similarly, the design must maximize the performance by strictly controlling the electrical properties of the loop while not eliminating its cost effectiveness. The designs will be analyzed using finite element analysis to assure that they are sufficiently rugged to withstand the difficult installation and operations environments.

Prototype designs include a high sensitivity flat cable loop suitable for installing in saw cuts and a round cable loop suitable for pave over installation. Preliminary production runs to assess manufacturing feasibility are now underway and field tests of the pilot loops are being conducted.

Please note that the designs discussed in this paper are currently in the process of being patented.

2 Concepts

The design concepts are system level ideas about inductive loop sensors, their manufacture and installation that are motivated by system requirements. These design concepts lead to design requirements

2.1 Product as a Goal

Since the original proposal, ORINCON has viewed the Advanced Preformed Inductive Loop Sensor project as a product development effort. When setting out to develop a product that replaces an existing product, several requirements are automatically in place. First and foremost, the product has to be an affordable option to the existing product. If the new product is initially more expensive than its competitor, then the added features must make it more cost effective in a broader scope.

In the case of the Advanced Preformed Inductive Loop Sensor, ORINCON knew that existing preformed loop sensors are expensive, and the reasons for the expense are clearly a result of their design. Therefore, for an advanced preformed loop sensor product with applications similar to existing sensors, ORINCON is confident that a superior sensor can be produced at a lower cost.

However, existing preformed loops are designed to be installed under new road surfaces such as an asphalt overlay. ORINCON saw that a much larger market exists for preformed loop sensors that are designed to be installed in saw-cut installations. In this application a preformed sensor would be competing against sensors that are wound in the field with very low cost loop wire. From cost estimates of the ORINCON preformed loop it is clear that the initial cost is higher than the equivalent quantity of loop wire. To make the ORINCON product attractive, the increased reliability, ease of installation, and increased performance must outweigh the initial cost of a loop sensor.

2.2 Improved Reliability

The concept of pre-manufacturing loops for improved reliability has been evolving now for a number of years. This concept comes in two areas:

1) Pre-winding the loop in the shop, and

2) Using heavier duty loop insulation.

Pre-winding the loop in the shop is a quality control measure. It assures that the wire is of the correct size and number of turns. Heavier duty loops are a reliability measure. Illinois DOT was an early advocate of encasing insulated loop wire in a vinyl plastic tubing. Donald Burmeister presented “Installation Innovations for Environmental Protection of Inductive Loops” at the 1979 Annual Meeting of ITE. The key element of this approach was to encase the wire in a way which allowed it free movement, providing protection due to pavement shift and faulting- NOT to protect the wire from direct physical damage. A second form of preformed loop developed during the late 70’s and early 80’s was the PVC pipe (1/2” diameter) encased loop, shown in Figure 1 below. This provided much tougher physical protection than the simple plastic tubing. The main difficulty of these concepts is that they are harder to install.

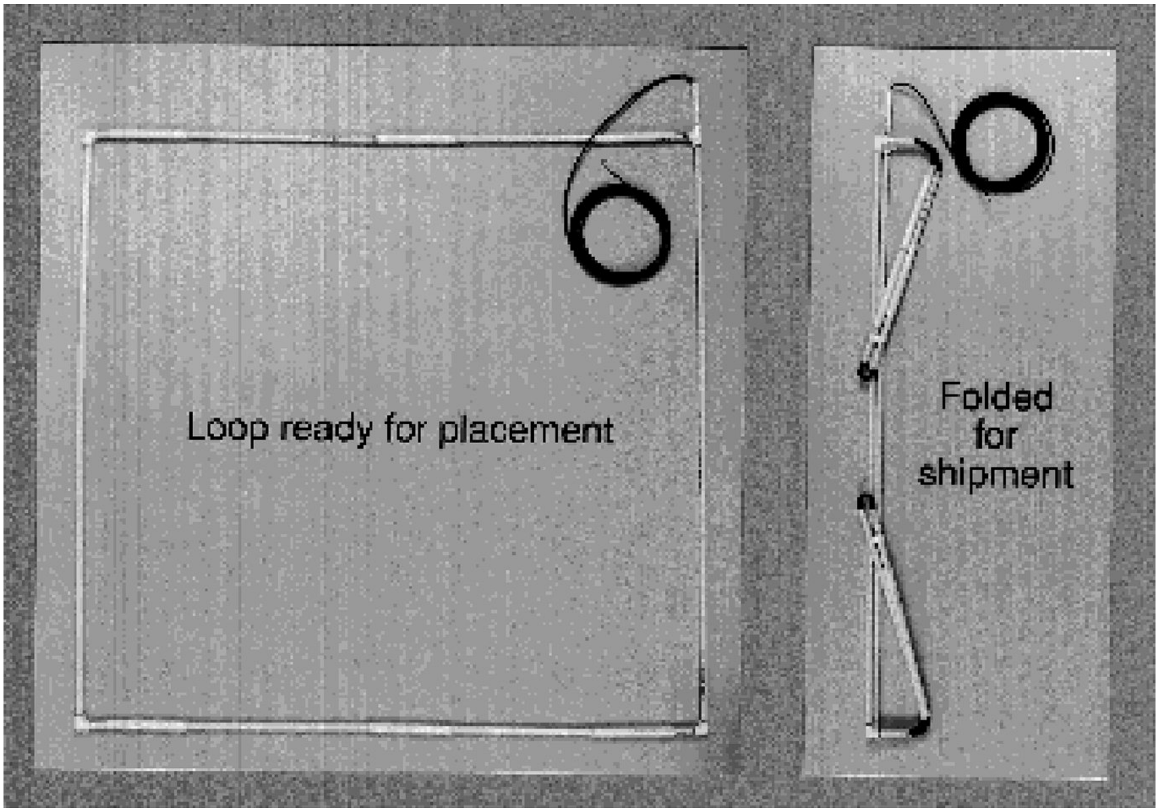


Figure 1 PVC Pipe Encased Preformed Loop

For the ORINCON Advanced Preformed Inductive Loop Sensor, both pre-winding and heavy insulation have been considered as important requirements for the product design.

2.3 Ease of Installation

For both pave-over and saw-cut loop sensors, proper installation is the most critical factor when considering reliability.

To help ensure a good *pave-over* loop installation, the sensor must have three properties:

1) First, it must be rugged to withstand being run over by heavy construction vehicles.
2) Second, it must be low profile to avoid being caught on asphalt spreading equipment and also to allow thin overlay layers.
3) It must be made of high temperature material to withstand molten asphalt.

To help ensure a good *saw-cut* installation, the sensor must have four properties:

1) First, it must be rugged to withstand sharp edges inside of the saw-cut, and truck traffic.
2) It must fit within a ¼” saw-cut to be consistent with common saw-cutting equipment and procedures.

3) It must have an adjustable loop head size because saw-cut loop perimeters are seldom perfect.

4) It must be made of high temperature material to withstand molten asphalt sealants.

By fulfilling the requirements enumerated above, a preformed loop design can make the installation process easier, and therefore generally increase the quality of loop installations.

2.4 Better Sensor Performance

By controlling the constituent materials, the geometry and the manufacturing process it is possible to create a loop which has very specific electrical characteristics. Existing loop sensors, both preformed and saw-cut, lack consistency in their relative wire spacing that leads to irregular performance. Pave-over preformed loops have irregular loop wire spacing inside of the loop head conduit. Saw cut sensors have both irregular loop wire spacing, and frequently do not have twisted lead wires. Also, loops formed in the field often have an incorrect number of turns, and frequently are at the wrong depth. ORINCON's design concept is to control the conductors' geometry to make more consistent, better sensors.

2.5 No Conduit

One of the advantages of a manufactured preformed loop as opposed to one that you assemble in the shop, is that it is possible to mold the materials of the preformed loop rather than placing the preformed loop in pipe or conduit. While pipe or conduit can be made very rugged, these materials are typically very rigid. This results in preformed loops that are much more difficult to carry out to the field. The pipe/conduit material is also much thicker. The large conduit requires a larger saw cut for non pave-over installations, frequently in the range of 1 inch. The requirement for the ORINCON designs are therefore that the ruggedness afforded by the conduit must be incorporated into the cable jacket, making the loop flexible and tough at the same time.

3 Design

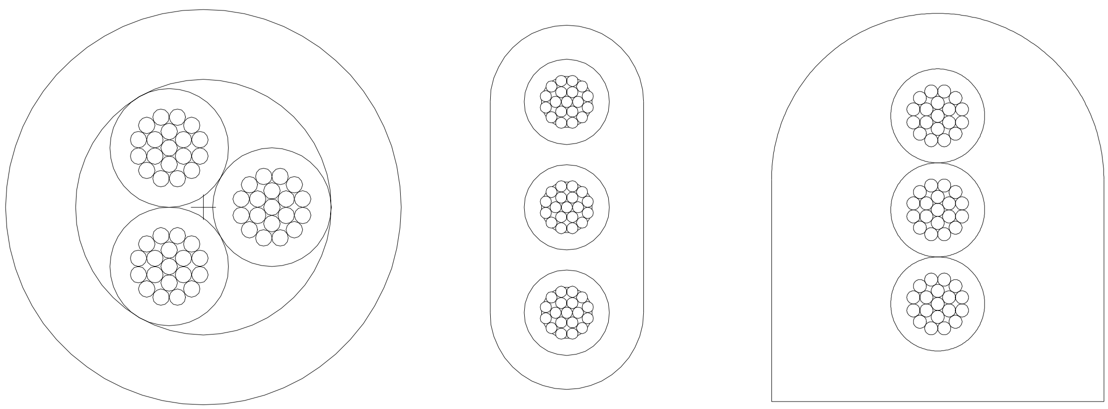
ORINCON's advanced preformed inductive loop sensor designs follow the requirements set out by the concepts described above.

3.1 Two Basic Designs

The first and most fundamental design decision was to create two basic designs, one for saw-cut installations and one for pave-over installations. This decision was based primarily on one requirement; that a preformed loop that is installed in a saw cut must be narrower than ¼ inch. Imposing this geometric requirement on a pave-over sensor seriously compromises its ruggedness.

3.2 Consider Several Geometries

For both the pave-over and the saw-cut designs, the loop head cable can be constructed in two ways. First it could be a round cable with conductors that are twisted together (cabled), or it could be a cable of parallel conductors that stack on top of each other. The reason for considering the parallel conductor geometry is to improve sensor sensitivity by increasing the length of the coil. To have parallel conductors stacked on top each other for the pave over design does require that the cable is not flat because that geometry would not stand vertical when the paving machinery runs it over. The three loop head cable cross sections that were considered are shown below in Figure 2 A, B, & C.



A B C

Figure 2

The flat cable cross section shown in Figure 2 B above is a natural choice for saw-cut loop sensors because of its narrow cross section. A round cable could be made with the required dimensions, however it would be significantly weaker and have poorer sensitivity. For the pave-over design, the cross section shown in Figure 2 D has superior sensitivity to a round cable, and has the desired ruggedness and rollover stability, however it is expensive and difficult to manufacture. The final decision, therefore, is to use a round cable with cross section shown in Figure 2 A for the pave-over sensor, and to use a flat cable with cross section shown in Figure 2 B for the saw-cut sensor.

3.3 Molded Connector

The ORINCON designs require splicing the loop wires inside of the junction between the loop head and the lead-in cable. The protection of that junction is therefore of particular concern when designing the sensor.

One of the major reasons for failure of splice joints is water intrusion. If splice joints have been sealed incorrectly, then water can get to the conductors and short the circuit. The three most common methods of splicing joints are to:

1) Cover the splice with electrical tape,
2) Cover the splice with heat shrink tubing and
3) Completely encapsulate the splice in sealant

Electrical tape has been found to be the least resistant to moisture penetration and requires coating the tape with a water-resistant compound to have a reasonable chance of success. Heat shrink tubing alone is a better method than electrical tape alone, but still lacks reliability. The third method is called the "Pill Bottle Splice" in the Traffic Detector Handbook and is formed by placing the wire splice into a small container filled with insulating material.

By creating a molded, preformed junction around the splice, a fourth method opens up. That is to encapsulate the entire connector in the mold creating one continuous seal which is totally resistant to moisture penetration and very resistant to damage. This joint is equivalent to the encapsulated joint and requires no extra skills on the part of the installation technician since it is not done in the field.

The original design concept proposed in the Phase I SBIR proposal was that the interconnection between the loop head and the lead-in cable would be encased in an injection molded housing of the same material as the cable jacket. That concept has come to reality with the designs that are being prototyped for this project. To form the loop, the wires of the loop and lead-in cables are appropriately spliced, and that intersection is put into an injection molding tool. The tool firmly seals off all of the cables that exit the intersection, and molten plastic is injected into the cavity of the mold tool. The hot, liquid plastic re-melts the ends of the cable jacket, and welds the entire intersection into a solid piece. The injected plastic is forced into the mold cavity with such force that it actually travels into any gaps in the cable cross section and further seals the wire splices.

The pave-over sensor's molded connector is shown below in Figure 3, the saw-cut sensor's molded connector is shown in Figure 4.

3.3.1 Figures of both Connector Designs

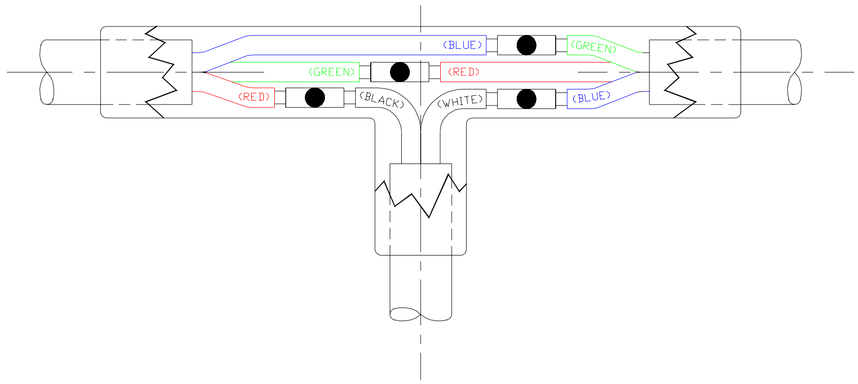


Figure 3 Pave–Over Loop Molded Connector Design

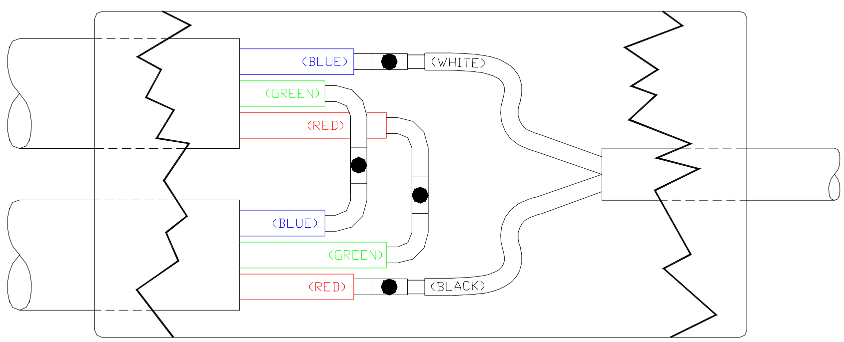


Figure 4 Saw-Cut Loop Molded Connector Design Drawing

3.4 Final Saw-Cut Sensor Design

The final saw-cut sensor design is shown below in Figure 5. This design is constructed of a loop head cable that has three primary conductors in a flat cable geometry. Each primary conductor is insulated in cross-linked polyethylene. The cable jacket is polyurethane. The lead-in cable is an unshielded twisted pair cable with the same insulating materials as the loop head cable. This lead-in cable is designed such that it can be run all the way to the detection electronics from where the loop is installed. Installation in this way removes the possibility of failure of the splice at the roadside junction box. The two ends of the loop head cable and the twisted pair lead-in cable enter a molded junction in the middle of the picture. After the loop is molded together, the entire assembly is cross linked to change the thermoplastic resin into a thermoset resin. This greatly increases the loops temperature resistance and mechanical strength.

It is very important to note that the molded junction sits in the *lead-in* saw-cut, not in the loop saw-cut. This allows a preformed loop sensor with a set loop head size to fit into saw-cuts with varying perimeters. Adjusting the loop head in this way means that no change in the saw cutting process is required, only a change in the cable that is put in the slot.

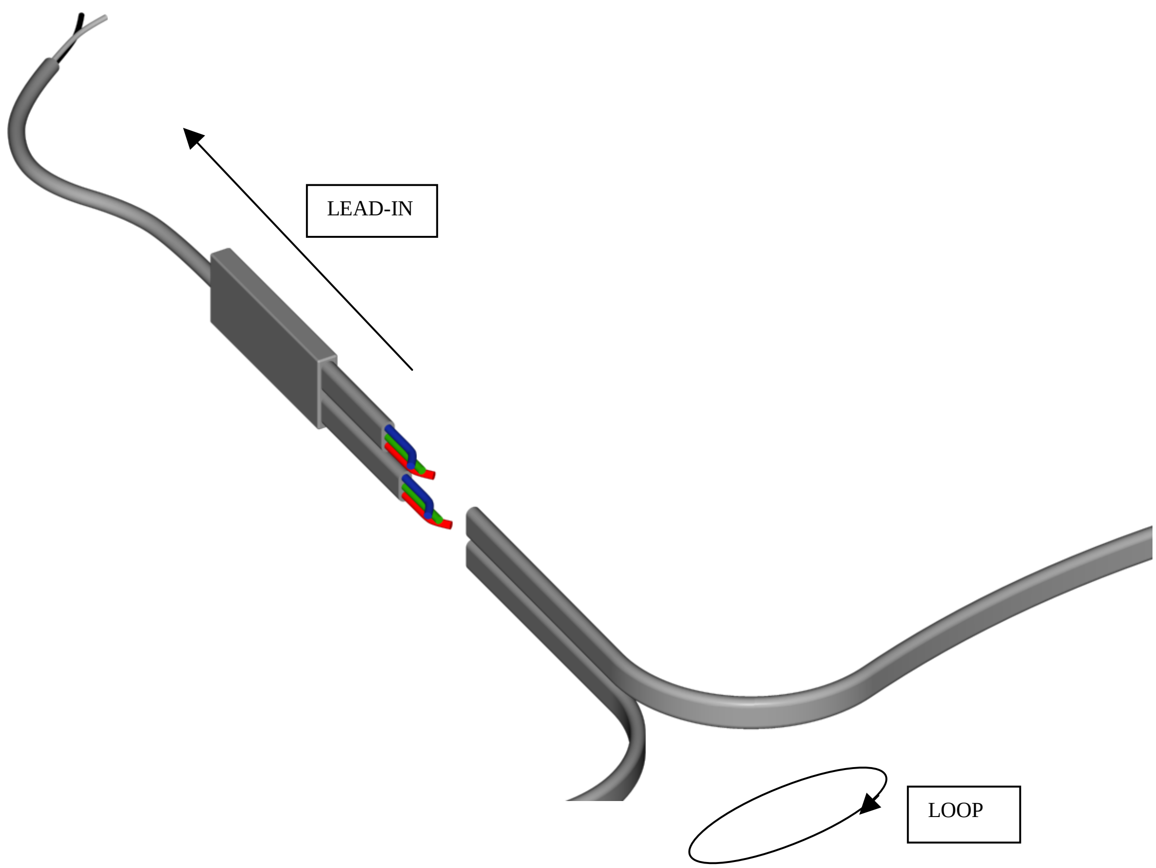


Figure 5 3D rendering of ORINCON saw-cut sensor design

3.5 Low Profile Pave-Over Sensor

The final pave-over sensor design is shown below in Figure 6. This design is constructed of a round cross section loop head cable that has three primary conductors. Each primary conductor is insulated in cross-linked polyethylene. The cable jacket is polyurethane. The lead-in cable is an unshielded twisted pair cable with the same insulating materials as the loop head cable. Construction of this loop is similar to that of the saw-cut loop.

This pave-over sensor's main design features are that it is very rugged, and that it is low profile. The ruggedness comes from a very heavy polyurethane jacket on the cables, and a heavy molded connector. Having a low profile pave-over loop sensor is important because one of the main problems with current pave-over preformed loop sensors is that they have large junctions between the pieces of conduit. These large junctions get caught on the paving equipment when the sensor is being covered.

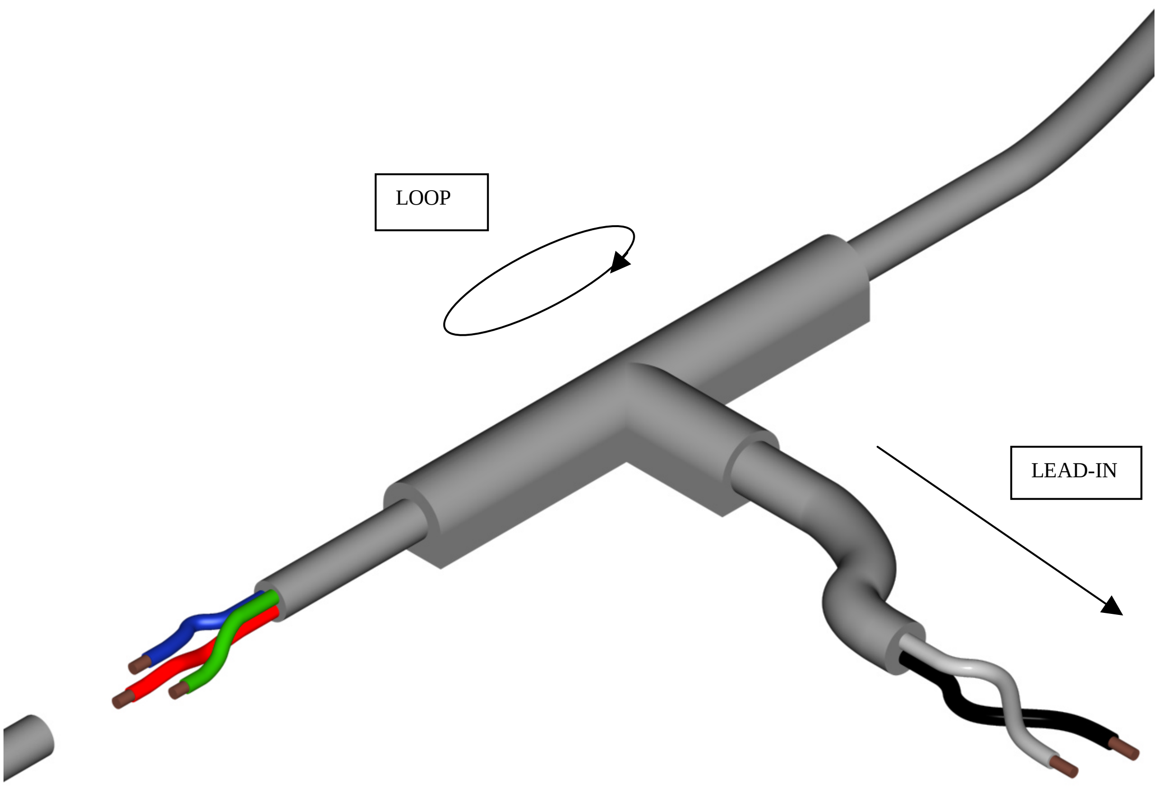


Figure 6 3D rendering of ORINCON pave-over sensor design

4 Finite Element Mechanical Analysis

Having completed the cable designs, the dimensions were then available to do a preliminary finite element mechanical analysis. The following section summarizes that preliminary analysis.

The objectives of the initial analysis were to:

1) Determine if the cable can withstand being run over by a construction vehicle
2) Determine if materials of construction are appropriate for the application
3) Identify failure modes and improve design if possible

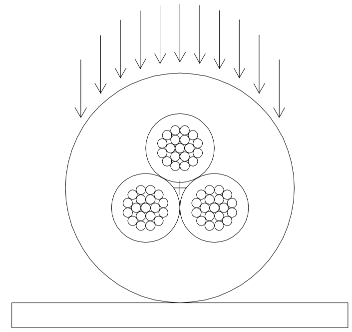


Figure 7 Loading of Cable

The model is generated by creating a mesh for each material and combining them into a single document, see Figure 8. The stranded copper conductors are meshed as solid. The polyethylene insulation is meshed as a continuous piece to accurately model the deformation of the three insulators, while accommodating the inability of the software to handle surface to surface contact. These approximations have been shown to faithfully represent the real system.

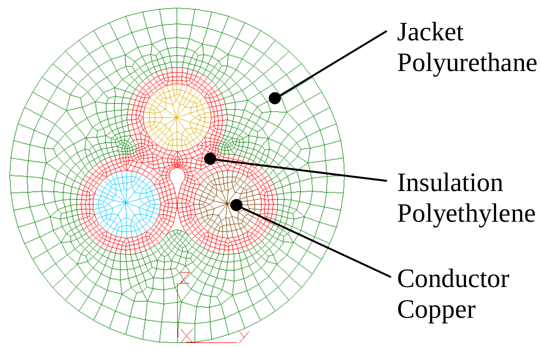


Figure 8 Materials and Mesh

All materials were modeled using the Von Mises yield condition. This model prescribes that each material exhibits a linear stress-strain response up to the yield point, this slope is familiarly known as Young's Modulus. Beyond the yield point the material again exhibits linear response but at a reduced stiffness known as strain hardening modulus. The overall material response through the yield point is nonlinear. The transition from the Young's Modulus to the strain hardening modulus is handled within the FEA software. This material model is specifically chosen for the plastics which generally exhibit this stress-strain response.

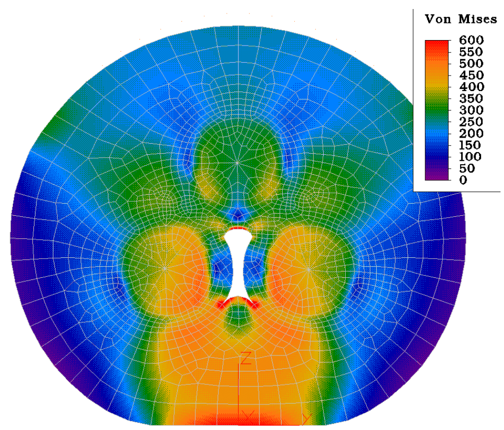


Figure 9 Von Mises Stress

The pressure extruded round pave-over cable withstands a 200 psi vertical load (see Figure 7) without exceeding the yield stress of the insulation, jacket or the copper conductor. Refer to Figure 9 for the maximum stress generated in each material. As the cable deforms under the load most of the stress is concentrated in the jacket material at and above the contact area. The highest stress is experienced at the bottom of the model where contact is made with the road surface. The model exhibits a very high degree of symmetry and smooth stress contouring. This indicates good mesh uniformity.

Accuracy of this model is acceptable, generally with an error of less than 1%, but with small areas exhibiting an error of about 20%, see Figure 10. The error hotspots are due to two reasons, intimate contact of two dissimilar materials, and sharp edges in the modeling. These hotspots do not significantly affect the results or conclusions drawn from the analysis. Stress at a node is calculated as an average of four data points, each data point lies just inside one of four quadrilaterals which form a node. Precision is the amount disagreement of these four data points. Precision is preferably below 10%, but is acceptable up to about 20%. At the boundary of two different materials the calculated stress will be higher in one material than the other, this is reported as a higher error. Sharp corners form a discontinuity in the stress calculation which technically would result in infinite stress at that point. The software compensates but since there are only one or two elements with which to calculate stress, the result is increased error.

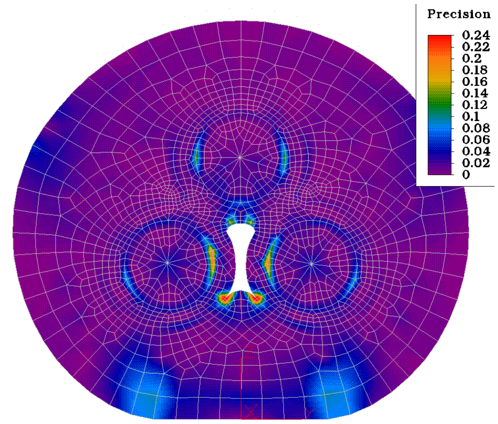


Figure 10 Precision of Model

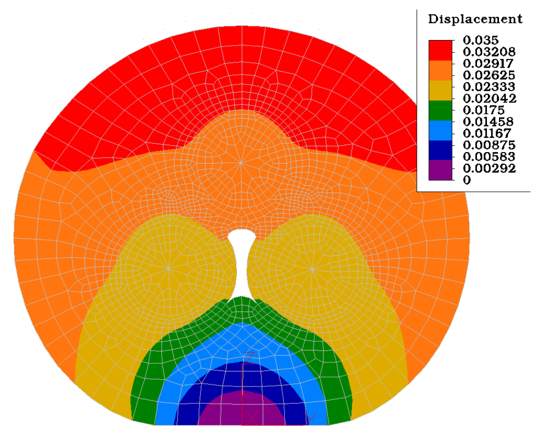


Figure 11 Displacement of Model

In addition to stress and precision plots, a plot of displacement, see Figure 11, is informative. Most importantly, there are no displacement discontinuities and the model again is highly symmetric. Also note that the levels of precision are sufficiently low as to not effect accuracy of the displacement calculation.

If the load were increased beyond 200 psi it is predicted that the plastic insulation surrounding the copper will experience stress approaching the yield point. As the load further increases the insulation will yield and flow away from the contact areas. This could lead to a failure only if the load is high enough to cause shorting of the conductors. Such a load is predicted to be unreasonably high for consideration as a failure mode. Combined stress-strain and flow analyses are beyond the capabilities of Algor FEA software that is being used. The predicted failure mode is puncture by a sharp object. If the jacket and two conductors are punctured this leaves the sensor susceptible to shorting out or intermittent operation in a chemical environment.

The materials chosen for this cable are appropriate to withstand being run over by a construction vehicle. Testing is currently under way to determine the puncture resistance properties of these materials and compare these results to other plastics. Based on preliminary data and look-up tables we anticipate the polyurethane and polyethylene will exhibit outstanding puncture resistance properties and therefore will prove to be appropriate materials.

5 Prototype

The Advanced Preformed Inductive Loop Sensor project is currently at the end of the prototyping phase. Prototype cables are made, and the injection molding process is currently going through some final adjustments. No complete sensors are available at conference time, but should be made shortly.

5.1 Custom Cables

Judd Wire, a manufacturer of wire and cables was contracted to create the prototype cables to ORINCON's specifications. Actually, several cables were made for evaluation and several have been ruled out due to manufacturability issues. The prototype cables chosen to continue in the prototyping phase of the project are shown below in Figure 12. Also in Figure 12 is the un-molded interconnection of the pave-over loop.

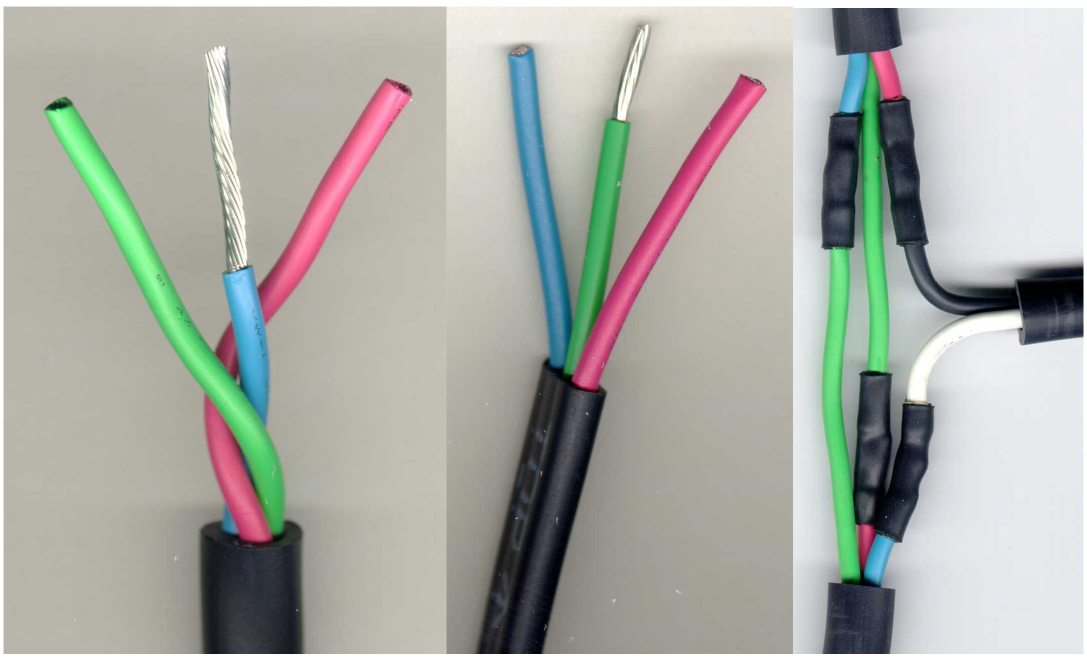


Figure 12 Prototype Round, Flat and Interconnection (round)

5.2 Custom Molds

ALD Industries, a molded cable assembly manufacturer has been contracted to do the assembly of the loops for this project. Currently the assembly process is almost complete. A few issues regarding details of the molds are being worked out. Once complete, ORINCON is confident that the sensors will perform as predicted.

6 Testing

ORINCON has started the testing phase of the Advanced Preformed Inductive Loop Sensor project. Currently only the chemical and mechanical testing of insulation materials has begun because the other tests require complete sensors.

6.1 Chemical and Mechanical Testing of Insulation Materials

Table 1 below shows the chemical and mechanical tests that are being performed on the materials that make up the ORINCON Advanced Preformed Inductive Loop Sensor. The first column is a brief description of the test, and the second column is the American Society for Testing and Materials (ASTM) standard test number for that test. Note that for three liquids - water, antifreeze and oil - there are three tests each:

1) Absorption

2) Young's Modulus and

3) Hardness

A full set of these tests is performed on each of the plastic materials used in the loop sensor. There are 3 different materials, one for the primary conductor insulation (cross linked polyethylene), one for the cable jacket (cross linked polyurethane) and one for the molded connector (also cross linked polyurethane).

Test Description	Standard Test Number
Young's Modulus (stress-strain)	ASTM D638 ASTM D412
Hardness	ASTM D2240
Low Temp Compression, 0 degC	ASTM D695
Low Temp Flexural Strength & Modulus, 0 degC	ASTM D790
Water, 23-25 deg C. (test at equilibrium)	ASTM D543
Young's Modulus, stress-strain (test at equilibrium)	ASTM D638 ASTM D412
Hardness (test at equilibrium)	ASTM D2240
Antifreeze, 23-25 deg C. (test at equilibrium)	ASTM D543
Young's Modulus, stress-strain (test at equilibrium)	ASTM D638 ASTM D412
Hardness (test at equilibrium)	ASTM D2240
ASTM oil #1 from ASTM D471. (test at equilibrium)	ASTM D543
Young's Modulus, stress-strain (test at equilibrium)	ASTM D638 ASTM D412
Hardness (test at equilibrium)	ASTM D2240
Melt and Glass Temp	N/A

Table 1

These tests are designed to improve our knowledge of the materials properties so that future efforts in finite element modeling will have the precise parameters required to achieve high accuracy results. These tests are currently in progress.

6.2 Lab Testing of Loops

In addition to the material tests described above, two more laboratory tests are being performed on the Advanced Preformed Inductive Loop Sensor.

First, several samples of the product will be cycled between -40°C and +60°C five times. The samples will then be tested to determine if the sensors continue function after the temperature cycling. Also, the sensors will be inspected to see if the temperature cycling had compromised the integrity of the cable jacket, the molded connector, of the seal between the two.

Second, the seal between the loop cable jacket and the molded connector will be tested with pressurized water to determine what pressure will break the seal

These tests will begin shortly after samples are available; no results are available at this time.

6.3 Sealant Compatibility Tests

To test the ORINCON saw-cut sensor's compatibility with the various sealants used for saw-cut installations, several feet of sensor cable will be installed in a saw-cut and covered with at least three of the most frequently used sealants. The pavement will then be core cut to reveal the covered cable and any damage that was caused by the sealants.

6.4 Field Testing of Loops

Currently there are four sites established as field test sites for the ORINCON Advanced Preformed Inductive Loop Sensor.

The first site is local to ORINCON in San Diego. The City of San Diego has suggested a location where a pair of advance sensors have failed. ORINCON will contract an installation crew to install one ORINCON sensor and one traditional sensor. ORINCON will then have those sensors available to collect data. The test plan calls for intentionally driving a particular car around the block and collecting inductance profiles from both sensors. Comparison of the inductance profiles will give a good indication of the quality of the ORINCON sensor relative to the traditional saw-cut sensor.

A second site in Texas is a similar situation except that the sensors are pave-over sensors and that they will be installed on a bridge deck.

Both pave-over and saw-cut sensors will be installed next to competing technology in the Virginia Tech Smart Road. Comparison tests are planned similar to those described above. ORINCON also plans on studying the classification performance of the ORINCON sensor connected to the IDC IVS-2000 classifying detector. ORINCON developed the classification algorithms in the IVS-2000 and we are interested in the differences in classification performance between the Advanced Preformed Inductive Loop Sensor and traditional sensors.

The fourth site is in conjunction with a program that ORINCON is working for the FAA and the Air Force. One ORINCON sensor measuring 65' by 10' will be installed on a taxiway at Long Beach Airport, and several others will be installed at McDill Air Force Base in Florida. Both inductive signatures and classification performance will be measured at these sites.

7 Market Research

One of the major goals of the SBIR program is to produce a commercially successful product at the end of the research. In order to be successful, a marketing strategy is needed. This marketing strategy must be based on a realistic estimate of the potential market, who the potential customers are and what will drive them to buy the product.

ORINCON Technologies Incorporated (OTI), the commercialization branch of ORINCON Corporation, contracted Entrepreneurial Management Inc. to do a market research analysis of the Advanced Preformed Inductive Loop Sensor. Entrepreneurial Management Inc. is a private firm run by business school professors at San Diego State University (SDSU) and is staffed by MBA students from SDSU. For the Advanced Preformed Inductive Loop Sensor project, three MBA students did the market research work with the supervision of two professors.

7.1 Summary of Market Research Findings

The group's primary objectives were to:

- Assess the current market situation
- Evaluate interest in the new system and
- Address future strategic issues.

Background information was obtained primarily through Internet and library resources, while specific information was obtained through a comprehensive telephone questionnaire, which was administered to 47 of the largest cities in the United States.

The research indicated that inductive loops are the most prevalent traffic system in use. Competing technologies are emerging, but costs are prohibitive and cities require further testing before adoption. Also, cities tend to rely heavily on outside contractors. Approximately 47% of the cities surveyed indicated that they use contractors exclusively for the loop installation process. Only 14% of the cities surveyed installed loops themselves.

In terms of the sample population, 44 cities that responded to the survey had a total of 29,731 controlled intersections. Averaged across this sample, approximately 60% of these intersections are controlled with loops, or 17,838 loop monitored intersections. Additionally, a sample average of 14 loops per intersection was calculated, which leads to a total number of 165,842 loops currently in use. Using the calculated average replacement rate of 9%, there are roughly 14,900 loops that could potentially be replaced by the Advanced Preformed Inductive Loop Sensor each year within the sample of 44 cities.

Although, traffic engineers conceded that they did not see a pressing need for a new inductive loop system, after describing the ORINCON Advanced Preformed Inductive Loop Sensor to traffic engineers, 86% expressed an interest in trying the product. Since there is not a significant *pull* for the product, marketing efforts will need to focus on *pushing* the product into a nation-wide marketplace. This can be accomplished through a partnership with an existing traffic equipment manufacturer and/or a large-scale distributor, as well as by promoting the product concept through trade shoes and industry journals.

8 Summary

ORINCON has worked under both a Phase I and Phase II SBIR contract with the FHWA to design an Advanced Preformed Inductive Loop Sensor that accounts for the shortcomings of the current state of the art and include new features that come from a re-evaluation of the requirements of inductive loop sensing.

The designs apply to both pave-over and saw-cut inductive loop sensor installations. Pave-over installation of preformed loop sensors is an existing technology that ORINCON's design has improved. With current preformed loops, saw-cut installation is highly unusual due to the difficulty of the process. ORINCON has designed a sensor that can be installed easily in saw-cuts with virtually no change in the installation process except for the cable that is put in the slot. These designs are currently in the process of being patented.

The designs are in the process of being prototyped and tested. Tests will be conducted to confirm the material properties of the loop sensor, evaluate its temperature cycling resistance, and its sealant compatibility. Loops will then be installed in several sites around the country to evaluate the ease of installation and their sensing performance.

The project is scheduled to end in early 1999. At that time full results of testing will available, and a new product will be headed to market.