Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp. 2337 - 2348, 2005

NEW LOOP DETECTOR INSTALLATION GUIDELINES FOR REAL-TIME ADAPTIVE SIGNAL CONTROL SYSTEMS

Seung-Hwan Lee
Professor
School of Environ. and Urban System Eng.
Ajou University
San 5 Wonchon-dong, Paldal-gu, Suwon, Korea 442-749
Fax: +82-31-215-7604
E-mail: shlee@ajou.ac.kr

Youngtae Oh
Professor
School of Environ. and Urban System Eng.
Ajou University
San 5 Wonchon-dong, Paldal-gu, Suwon, Korea 442-749
Fax: +82-31-215-7604
E-mail: ytoh@ajou.ac.kr

Sangsoo Lee
Assistant Professor
School of Environ. and Urban System Eng.
Ajou University
San 5 Wonchon-dong, Paldal-gu, Suwon, Korea 442-749
Fax: +82-31-215-7604
E-mail: sslee@ajou.ac.kr

Abstract: A real-time adaptive signal control system, named COSMOS, generated signal control parameters automatically using collected information from loop detectors. Therefore, the reliability of loop detector information can affect the operational effectiveness of the signal control system. In this paper, a set of practical loop detector installation guidelines was developed through extensive field experiments. Results indicated that a laying depth of 12 cm provided good performance regardless of detector types tested. In addition, a laying depth less than 9 cm should not be selected in practice. The limit lengths of feeder cable were determined as 1,000 m for octagon loop detector and 900 m for circle loop detector, respectively. It was also recommended that the number of soldering should be less than 6 times when the feeder cable length was below 600 m, and 4 times when the length was in a range between 600 m and 1,000 m.

Key Words: Loop detector, Guideline, Signal control, Adaptive control

1. INTRODUCTION

A real-time adaptive signal control system, named COSMOS (Cycle, Offset, Split Model for Seoul), has been operated in many urban cities in Korea. Due to its functional richness and flexibility, it will be expanded in other cities throughout the nation. The systems collected real-time traffic data from loop detectors, and generated signal control parameters automatically using the collected information. Therefore, the reliability of loop detector information can affect the operational effectiveness of the signal control system. Recently, the effectiveness of the system has occasionally been reduced because of frequent breakage and malfunction of loop detectors. This is partly because this is no standard guideline or specification for uniform and consistent loop detector installation. In addition, there is no practical report or paper to deal with any procedures for proper operation. National Electrical Manufacturers Association (NEMA) provides some experimental results through tables and figures, but the results are not directly applicable because physical characteristics of the roadway systems in Korea are quite different (e.g., long link lengths).

Consequently, the detailed specifications of loop detector installation could vary in terms of worker's experiences or company's policies. This spatial inconsistency might affect the overall operational performance of the traffic control system, which is responsive to varying traffic demand. A research report indicated that the malfunction of loop detector operation was mainly attributed to inappropriate installation operation (Road Traffic Safety Association, 1994). Therefore, it is necessary to develop a set of uniform guidelines on loop detector installation to assist traffic engineers for obtaining consistently high quality of traffic data.

This study aims to develop a set of guidelines that may control overall procedures on loop detector installation for adaptive signal control systems. For this study, an extensive field study was performed as for the selected design of experiment. The installation guideline on laying depth of loop detectors was investigated. To identify any performance differences in terms of detector shape, three types of loop detectors were tested simultaneously: Octagon, quadrupole, and circle. The guideline on maximum length of feeder cable was developed from various experimental tests for different conditions. In addition, the current practice on the number of soldering of loop detector was evaluated, and some guidelines were made with consideration of feeder cable lengths. By applying these guidelines, it is expected that the signal control systems have uniform and reliable detector information throughout the nation. Therefore, the operational performance of the system can be improved significantly.

In this paper, firstly, the current practices on loop detector installation will be briefly described. Secondly, the elements of experimental design will be discussed. Next, the test results will be discussed as well as statistical analysis results, and the guidelines will be described. The last chapter concludes this study.

2. BACKGROUD

2.1 Theory

A loop detector detects the passing or existence of a vehicle from change in the rate of the inductance of the loop coil buried on the roadway when the vehicle passes or stops over the detection area (Klein, 2001). It provides traffic variables necessary for traffic signal control such as occupancy time, non-occupancy time, and departure volume. In general, a loop detector system is installed in accordance with NEMA standards, and it is primarily consists of a loop coil, a lead-in cable and a detection device unit (ITE, 1992). The typical configuration of loop detection systems is shown in Figure 1.

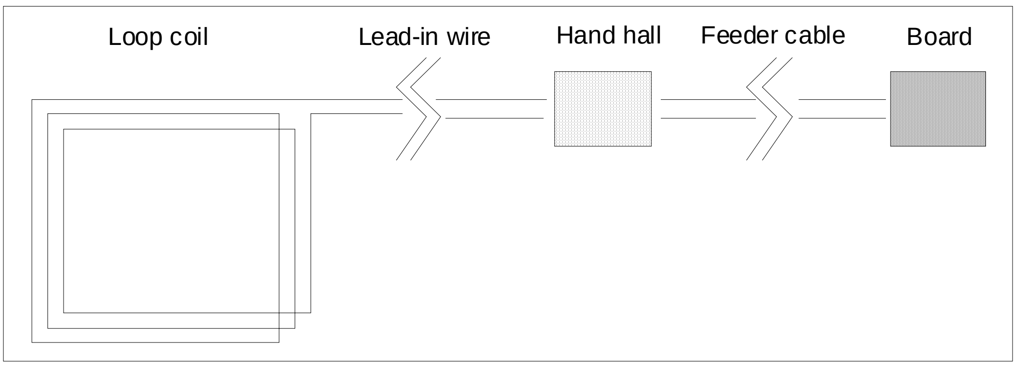

Figure 1. Configuration of Typical Loop Detection System

The loop coil is laid down on the lanes of a roadway, generally by use of annealed copper wire AWG No. 14 of diameter 4 to 5 mm turned twice to four times. In Korea, the number of turns is set to three (Seoul Metropolitan Police Agency, 1998). The lead-in wire (or cable) interconnects the loop coil with the feeder cable inside the hand hall. The recommended specification of the lead-in cable for a quadrupole or an octagon loop detector is annealed copper wire AWG No. 14, and that for a circle loop detector is annealed copper wire AWG No. 14 or 16 with dual reinforced covering (Seoul Metropolitan Police Agency, 2000). The lead-in cable may interconnect the loop coil with the detection device unit directly if the distance between the two is short. The feeder cable is used to interconnect the lead-in cable with the detection device unit inside the local controller. In general, it is applied in case the distance between the two is long. The recommended specification of the feeder cable is annealed copper wire AWG No. 14 or 16 triple insulated.

Most substances such as air, insulator, wood and plastic are non-magnetic, but conductors are magnetic. The magnetic resistance of a magnetic substance is due to its physical property, and the magnetic resistance of the substance can be easily obtained from the following equation (ITE, 1992).

$$R^* = \frac{l}{A \times u} \tag{1}$$

Where:

R* : Magnetic resistance;
l : Length of the coil cross-section, m;
A : Cross-section of the magnetic circuit, m^2; and,
u : Permeability

In the loop detection system, the current flows through the loop coil buried on the roadway and the loop cable to the lead-in wire. Thus, the magnetic flux in proportion to a constant inductance value is created when there is no vehicle. When a vehicle passes on the magnetic field formed around the loop, the changes in magnetic flux between the vehicle and the loop coil take place. The magnetic flux of the loop coil and the induced flux interact with each other, and it brings about change in magnetic flux. Therefore, a magnetic field to the opposite direction of the change in magnetic flux is generated, and this magnetic field combined with existing magnetic field around the loop causes changes in inductance. The loop detector converts such changes in inductance to a function of frequency, and the existence of vehicle is detected through this process.

2.2 Current Practices in Korea

Currently, quadrupole, octagon, and circle loop detectors are installed for COSMOS operation in Korea (Oh and Lee, 1995, 1996). The quadrupole loop detectors are used for the measurement of degree of saturation (DS), and the dimension of a quadrupole loop detector is 4.0 m × 1.8 m. It is located on the two through lanes of the approach, and is installed close to the stopline. An octagon loop detector is used for the identification of queue lengths or level of congestion, and its dimension is 1.8 m × 1.8 m. The installation location of queue length detectors is determined between 100 m to 800 m behind the stop line depending on the link length and traffic conditions. For some sites, the octagon loop detector may be installed for spillback detection purpose, which is located within 60 m from the outlet of the crossroad. A circle loop detector is a good substitute for octagonal loop detector in terms of application purpose, only except for its dimension of 0.9 m diameter. Table 1 summarizes the specification and function of the three detectors (Seoul Metropolitan Police Agency, 1999).

Table 1. Detector Types in COSMOS

Types	Quadrupole	Octagon	Circle
Function	Degree of Saturation	Queue length or Spillback	Queue length or Spillback
Length	4.0m × 1.8m	1.8m × 1.8m	0.9m radius
Location	TH: stopline LT: 12m within stopline	Queue Length	100m - 800m setback from stopline
		Spillback	60m ahead of upstream intersection

Note: TH: through lane, LT: left-turn lane

The location of loop detectors for adaptive signal control systems should be determined based on the control strategy and geometric conditions. A typical layout of loop detection systems employed in COSMOS is shown in Figure 2.

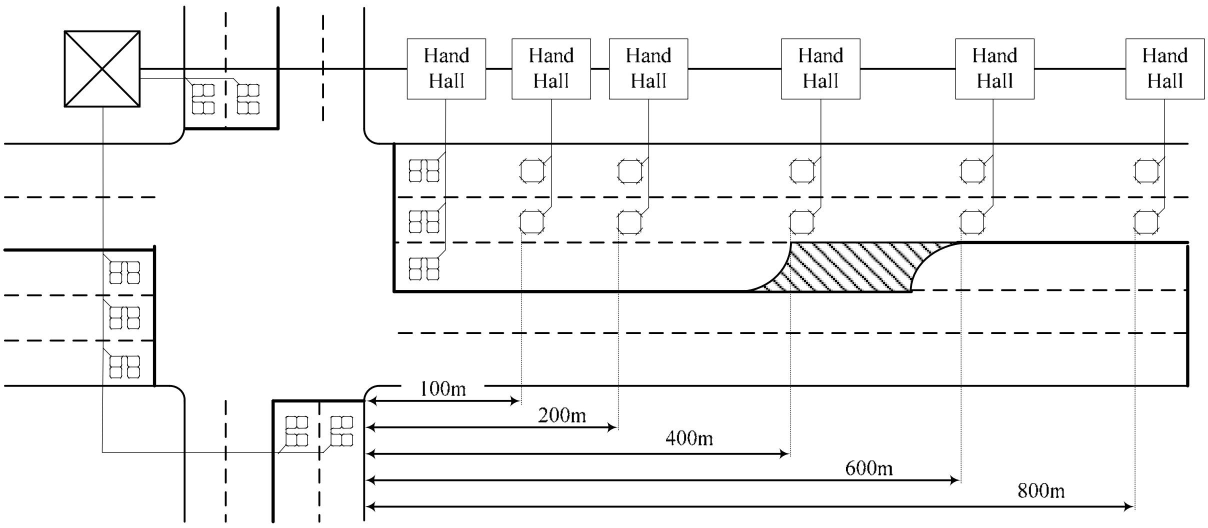

Figure 2. Layout of Loop Detectors in COSMOS

The total number of loop detectors installed in Seoul City as of the end of 2002 was 1,519 units, consisting of 552 quadrupole, 371 octagon, and 596 circular loop detectors. With regard to laying depths, octagon loop detector is buried in 9 cm deep while circular one is 12 cm deep. In case of quadrupole loop detector, it was buried 9 cm deep until 2002, but the burial depth had been increased to 12 cm due to frequent damage to those detectors caused by heavy vehicles and surface cutting work during resurfacing work.

Other major cities in Korea, such as Daegu, Daejeon, and Cheongju, use the same location and configuration of loop detectors for real-time signal control systems. However, the laying depths adopted by these cities are much shallower, merely from 5 cm to 7 cm for all types of detectors. As a result, the operating survival rate of loop detectors in these cities is much inferior to Seoul around 50% to 70% only. The main reason for this poor performance is assumed to be shallower laying depth. Besides, improper initial installation due to lack of standardized specifications and insufficient maintenance activities may be other reasons for high defect rates and low survival rate. The summarized statistics on loop detector operation are listed in Table 2. The breakdown rate in Seoul in 2002 is only 5.9%, which is a very good result as compared to other cities. This is partly because the laying depths in Seoul are far deeper than other cities. However, the optimum laying depths are still unknown from these statistics.

Table 2. Statistics of Loop Detector Operation

<table>
<tr><th>City</th><th colspan="2">Type of Detector</th><th>Laying Depth</th><th>Number</th><th>Breakdown</th><th>Breakdown Rate</th></tr>
<tr><td>Daegu</td><td colspan="2">Octagon, Quadrupole</td><td>5.0cm</td><td>850</td><td>252</td><td>29.6 %</td></tr>
<tr><td>Daejeon</td><td colspan="2">Octagon, Quadrupole</td><td>5.0cm</td><td>415</td><td>185</td><td>44.6 %</td></tr>
<tr><td>Chungju</td><td colspan="2">Octagon, Quadrupole</td><td>5.0cm</td><td>30</td><td>16</td><td>53.3 %</td></tr>
<tr><td rowspan="4">Seoul</td><td rowspan="2">Quadrupole</td><td>before 2002</td><td>9.0cm</td><td rowspan="2">552</td><td rowspan="4">90</td><td rowspan="4">5.9 %</td></tr>
<tr><td>since 2002</td><td>12.0cm</td></tr>
<tr><td colspan="2">Octagon</td><td>9.0cm</td><td>371</td></tr>
<tr><td colspan="2">Circle</td><td>12.0cm</td><td>596</td></tr>
</table>

Source: Internal Report, Board of Audit and Inspection of Korea, 2002

3. DESIGN OF EXPERIMENT

To conduct a field test, the scope of experiment should be determined. The pavement thickness of most major roadways was about 200 mm, and it was identified that cutting operation can be done within 50 mm at the time of resurfacing in order to minimize damage to buried loop detectors. With consideration of these pavement conditions and current practices, three levels of laying depths were selected for octagon and qadrupole loop detectors as 70 mm, 90 mm, and 120 mm, while laying depths of 90 mm, 120 mm, and 150 mm were tested for circular loop detectors.

The types of vehicles used for test were passenger car (PC) and recreational vehicle (RV). With regard to the dimension of the vehicles used for test, the total length and axle height of the RV were 4.8 m and 0.19 m, and those dimensions of the PC were 4.48 m and 0.16 m, respectively. The range of feeder cable lengths tested was varied from zero to undetectable distance. In addition the number of replication was set to five for each of given experimental conditions. The selected experimental elements are summarized in Table 3.

Table 3. Range of Experimental Elements

<table>
<tr><th>Item</th><th>Octagon</th><th>Quadrupole</th><th>Circle</th></tr>
<tr><td rowspan="3">Laying depth</td><td>70mm</td><td>70mm</td><td>90mm</td></tr>
<tr><td>90mm</td><td>90mm</td><td>120mm</td></tr>
<tr><td>120mm</td><td>120mm</td><td>150mm</td></tr>
<tr><td>Test car</td><td colspan="3">PC, RV</td></tr>
<tr><td>Replication</td><td colspan="3">5 times</td></tr>
<tr><td>Speed</td><td colspan="3">around 10 kmh</td></tr>
<tr><td>Feeder cable</td><td colspan="3">0 m – undetected length</td></tr>
</table>

The test site layout of loop detectors for this study was arranged for different detector configurations in terms of laying depths and detector types. The number of turns at the head of each loop detector was set to three. For the installation of loop detectors, the current practices were applied. The layout of field test site is shown in Figure 3.

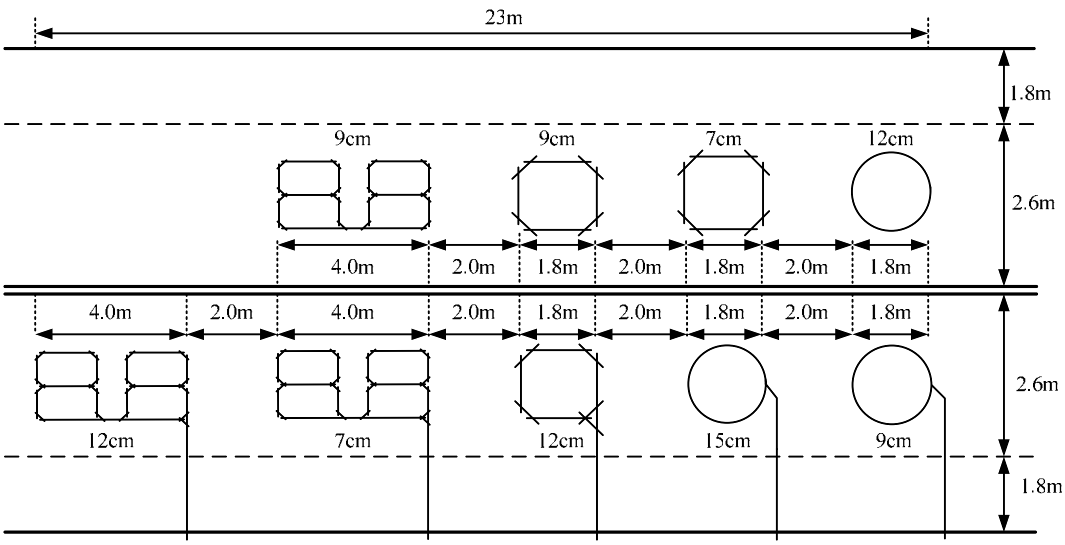

Figure 3 Configuration of Field Test Site

The clearance between loop detectors was kept at 1.8 m or farther considering potential mutual influence between adjacent loop detectors. A study indicated that a clearance distance of 0.6 m from a loop detector could be influenced by the next detector. Considering this fact and accepting recommendations given by NEMA, a distance of 0.8 m to 0.9 m or longer was secured from the end line of the loop detector to the adjacent lane. The specifications of each loop detector wire were the same as described in the previous section.

The test vehicle drove the center of each detector with a constant speed. As the test vehicle passed the detectors, the electronic outputs from the detectors were automatically recorded into a laptop computer. To verify the accuracy of data, each experimental condition was recorded with a video recorder, simultaneously. The test run was made in five times for each of experimental conditions.

4. ANALYSIS RESULTS

4.1 Data Collection and Analysis

The evaluation of the experiment for laying depth and feeder length limit was conducted using the data collected from both loop detector board and videotape. Theoretical occupancy time and measured occupation time were compared using the data, and vehicle detection rate was evaluated on the basis of a reference value. A 100% detection rate indicates that no error is observed between measured occupancy time and theoretical occupation time. That is, it can be said that the information of vehicles is detected accurately. Since the actual loop data could have random fluctuations around true value, the output values greater than the reference value should be accepted as true value with white noise. The arithmetic average values of detection rate were calculated from five test runs per vehicle.

For comparing the performance, absolute difference of the two detection rates was estimated on the basis of a theoretical reference value. It was considered that a measurement variation could be occurred during a frame analysis (1/30 second) of videotape. Therefore, the maximum error of 3 percents could be involved during the frame analysis. The significance of differences from the test results was identified through a statistical analysis.

4.2 Test Results

The results of detection rate according to laying depths and feeder cable lengths with quadrupole loop detectors were listed in Table 4. Observing the results, the maximum errors in detection rate for RV and PC is 0.9% and 5.6% at 7.0cm laying depth and without feeder cable connection. For other laying depths, the maximum errors were in a range from 1.0% to 2.6% for both types of vehicles.

Table 4. Detection Rates for Quadrupole Detector (%)

Type	Feeder Cable Length	Laying Depth		
		7cm	9cm	12cm
RV	0m	99.1	98.3	97.4
	100m	63.8	55.1	36.1
	300m	32.6	27.0	0
	600m	0	0	0
PC	0m	105.6	101.0	101.8
	100m	72.5	64.9	54.2
	300m	61.1	52.7	28.7
	600m	45.5	26.8	0

With feeder cables connected, detection rate fell down with increase in feeder cable lengths and burial depths because the sensitivity of loop detector was reduced. In addition, in comparing the magnitude of detection rates, the detection rate of RV was lower than that of PC, and non-detection began to occur when the length of the feeder cable exceeds 600m for all laying depths. This is because the axle height of RV is higher than that of PC. The results also indicated that the use of feeder cable with quadrupole detectors should be avoided as possible as it could. From these results, therefore, it can be stated that it is necessary to make a close inspection with cautions during a calibration process of detectors.

The current statistics show that most quadrupole loop detectors are connected to the loop detector board by use of lead-in wire only in Korea. That is, the detection rate results with feeder cables may be insignificant for most locations. However, the experiment results are important in developing a reasonable practice for other locations.

The results of detection rates for various laying depths and feeder cable lengths with octagon loop detectors were summarized in Table 5. From the results, it was found that the overall performance of octagon detectors in terms of varying feeder cable lengths was improved significantly as compared to quadrupole detectors. In terms of laying depths, no single laying depth gave the best detection rates for octagon loop detectors. The largest detection error was found to be 4.8% from both RV and PC, and most detection errors were located within 2.0%. The detection rates were significantly reduced for a feeder cable length exceeding 1,000 m. Therefore, it was not recommended to use a feeder cable length over

1,000m. This finding is practically reasonable because it is vary rare to find the highway systems exceeding link lengths of 1,000m in urban area.

Table 5. Detection Rates for Octagon Detector (%)

Type	Feeder Cable Length	Laying Depth		
		7cm	9cm	12cm
RV	0m	98.3	98.3	95.6
	200m	101.5	97.2	100.9
	400m	102.2	101.7	98.4
	600m	104.8	100.6	98.5
	800m	101.8	99.9	98.8
	1000m	99.3	102.3	102.5
PC	0m	103.2	95.6	97.5
	200m	101.5	99.1	101.1
	400m	100.4	103.2	100.3
	600m	100.6	95.2	98.4
	800m	101.5	99.3	100.9
	1000m	102.8	102.6	98.6

To identify the significance of detection rate differences, two-factor ANOVA analysis was performed (SAS, 1988). The two factors considered were feeder cable length and laying depth. Analysis results of RV for octagon detectors were listed in Table 6. From the results, it was identified that the feeder cable length was a significant factor. However, the laying depth was not a significant factor at the 1% significance level. This fact also indicates that the variability of detection rates from different laying depths shown in Table 5 is statistically insignificant.

Table 6. ANOVA Results from RV for Octagon Detector

Source	SST	DF	MSE	F value	P-value
Length	163.3	5	32.65	4.252	0.0019
Depth	74.53	2	37.26	4.853	0.0105
Interaction	208.0	10	20.8	2.709	0.007
Error	552.8	72	7.68		
Total	998.6	89			

The overall error trends for octagon detectors were shown in Figure 4. It should be noted that the results from laying depth of 12 cm provided the better results than other laying depths in terms of high frequency of the best results for experimental conditions tested. The identical results could be obtained from the test results of PC. Therefore, it can be said that the laying depth of 12 cm is a good practice. This guideline is also reasonable and consistent with a current practice.

The results of detection rates for various laying depths and feeder cable lengths with circle loop detectors were listed in Table 7. From the results, it was also identified that the overall performance of circle detectors in terms of varying feeder cable lengths was significantly improved as compared to quadrupole detectors. Although the magnitude of error rates increased slightly as compared to octagon loop detectors, the variability of the test results was in a reasonable range. Likewise, no single laying depth produced the best detection rates for circle loop detectors. The largest detection error was observed as 8.2% at feeder cable length of 600 m for RV. However, reasonable detection errors were observed from the most of experimental conditions. The upper limit of feeder cable length for circle loop detectors was identified as 900 m. This is because non-detection occurs when the feeder cable length exceeds 900 m.

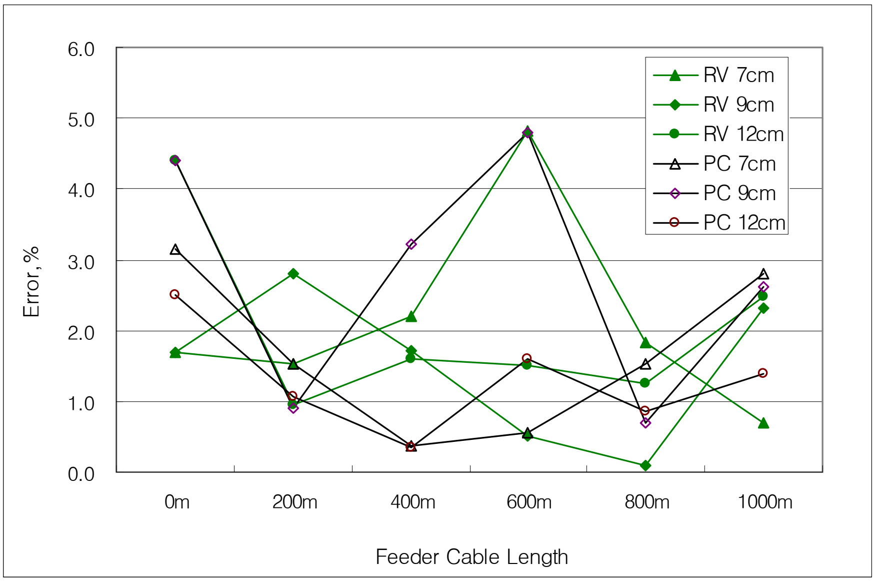

Figure 4. Detection Errors for Octagon Detectors

Table 7. Detection Rates for Circle Detector (%)

Type	Feeder Cable Length	Laying Depth		
		9cm	12cm	15cm
RV	0m	97.5	101.3	101.5
	200m	101.5	97.6	100.6
	400m	100.4	106.9	100.9
	600m	108.0	108.2	99.3
	800m	103.2	102.4	102.7
	900m	106.2	106.5	100.6
PC	0m	99.2	97.6	100.9
	200m	101.8	102.3	99.6
	400m	101.4	96.5	99.8
	600m	100.8	98.0	102.3
	800m	103.3	100.6	101.7
	900m	102.0	106.6	98.2

For the circle loop detectors, an identical two-factor ANOVA analysis was performed to verify the significance difference of detection rates (SAS, 1988). Analysis results of PC for circle detectors were listed in Table 8 with two factors, feeder cable length and laying depth. From the results, it was identified that the feeder cable length was a significant factor. However, the laying depth was not significant factor at the 1% significance level. Therefore, the similar conclusions can be drawn with the test results from octagon detector.

Table 8. ANOVA Results from PC for Circle Detector

Source	SST	DF	MSE	F value	P-value
Length	130.1	5	26.02	4.320	0.0017
Depth	24.56	2	12.28	2.039	0.1375
Interaction	327.05	10	32.70	5.431	0.0001
Error	433.58	72	6.02		
Total	915.29	89			

The overall detection error trends for circle detectors were shown in Figure 5. In terms of frequency of the best outputs, both laying depth of 15 cm and 12 cm provided the good results as compared to laying depth of 9 cm.

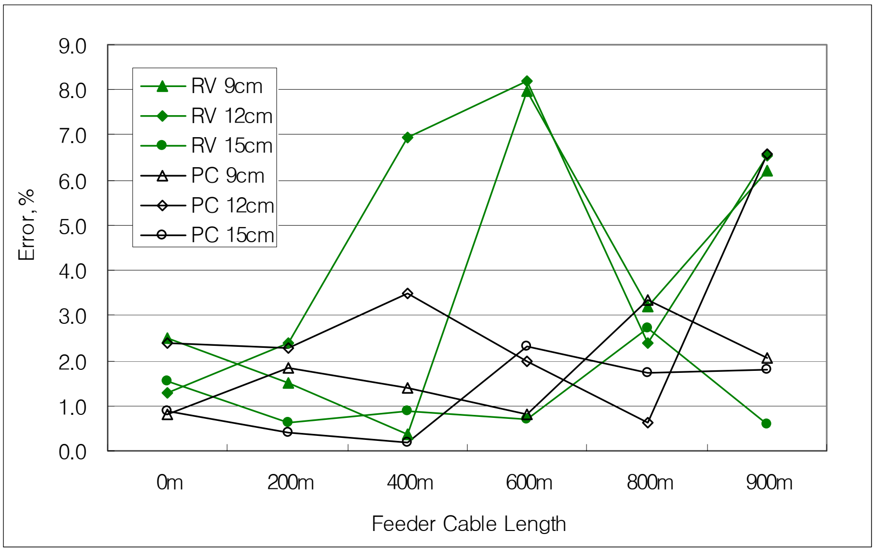

Figure 5. Detection Errors for Circle Detectors

To develop a guideline on the number of soldering of feeder cable and lead-in cable, the electronic characteristics of each loop detector were tested (ITE, 1992). The test results were summarized in Table 9.

Table 9. Test Results of Electronic Characteristics

Type	Number of Soldering	Frequency, KHz	Inductance, uH	Resistance, Ω	Quality
Octagon	0	50	79.5	1.4	18.2
	1	50	79.4	1.4	17.8
	2	50	79.9	1.4	17.6
	3	50	80.5	1.5	17.2
Circle	0	50	76.2	2.7	8.7
	1	50	75.6	2.7	8.9
	2	50	75.9	2.7	8.8
	3	50	76.2	2.8	8.7

As shown in the table, the quality of detector systems was not significantly changed in terms of number of soldering for both types of detectors. For the octagon detector, the quality value was 18.2 with no soldering while the quality value was slightly reduce to 17.2 with three times of soldering. However, both quality values were far higher than the recommended values given by NEMA. Applying the test results shown in Table 9 and considering current practices, a guideline on number of soldering was developed as listed in Table 10. The guideline stated that the number of soldering should be less than 4 times when the feeder cable length was in a range between 600 m and 1,000 m. In addition, the soldering number could increase up to 6 times when the feeder cable length was less than 600 m.

Table 10. A guideline on Number of Soldering

Feeder Cable Length	Number of Soldering			
	Lead-in Cable + Lead-in Cable	Lead-in Cable + Feeder Cable	Feeder Cable + Feeder Cable	Total
Below 600m	2 times	1 time	3 times	Within 6 times
Over 600m	2 times	1 time	1 time	Within 4 times

5. CONCLUSIONS

In this paper, a set of guidelines on loop detector installation for adaptive signal control systems was developed through extensive field tests. To identify performance differences from detector shapes, three types of loop detectors were tested simultaneously. Test results were also discussed with statistical test outputs.

It was identified that the effects from laying depths were not statistically significant for both octagon and circle loop detectors. From the results, it was found that the use of a laying depth of 12 cm could provide good detection rates regardless of detector types. In addition, a laying depth less than 9 cm should not be selected for a practical application. For the guideline on the limit lengths of feeder cable, the test results indicated that the limit length of feeder cable was 1,000 m for octagon loop detector and 900 m for circle loop detector, respectively. For the guideline on the number of soldering, the test results showed that the number of soldering should be less than 6 times when the feeder cable length was below 600 m. Further, the number of soldering was less than 4 times when the length was in a range between 600 m and 1,000 m.

The test results were consistent with the recommendations given by NEMA, but the scope of this study was expanded in order to consider different roadway characteristics such as long link lengths and pavement conditions in Korea. The guidelines presented in this paper are very useful for practical application, and the results can be adopted for other countries' practice. It is expected that the use of proposed guidelines can contribute for improving operational performance of the real-time adaptive signal control systems.

REFERENCES

1. Institute of Traffic Engineers (1992) **Traffic Detector Handbook 2nd edition**, ITE, Washington D.C.
2. Klein, L. A. (2001) **Sensor Technologies and Date Requirements for ITS**, Artech House, Boston, MA.
3. May, A. D. (1990) **Traffic Flow Fundamentals**, Prentice-Hall, Englewood Cliff, N.J.
4. McShane, W. R. and Roess, R. P. (1990) **Traffic Engineering**, Prentice Hall, Englewood Cliff, N.J.
5. Oh, Y. and Lee C. (1995) The Decision of the Optimal Shape of Inductive Loop Detector for Real-Time Signal Control, **Journal of Transportation Research Society of Korea, Vol. 13**. No. 3, pp. 67-86.
6. Oh, Y. and Lee C. (1996) Evaluation of Confidence of Vehicle-Detector Information for Real-Time Traffic Signal Control, **Journal of Transportation Research Society of Korea, Vol. 14**. No. 3, pp. 91-125.
7. SAS Institute Incorporated (1988) **SAS/STAT user's Guide, Release 6.03 Edition**, Cary, N.C.
8. Seoul Metropolitan Police Agency (1992) The 2nd Year Development of Traffic Signal Control System Methodology, National Police Agency, Korea.
9. Seoul Metropolitan Police Agency (1998) NEMA Specifications for Traffic Signal Control Systems, National Police Agency, Korea.
10. Seoul Metropolitan Police Agency (1999) A Final Report on The 1st Functional Improvement of Adaptive Traffic Signal System of Seoul, National Police Agency, Korea.
11. Seoul Metropolitan Police Agency (2000) A Final Report on The 2nd Functional Improvement of Adaptive Traffic Signal System of Seoul, National Police Agency, Korea.
12. Seoul Metropolitan Police Agency and Road Traffic Safety Association (2000) An Executing Drawing for 2000 Adaptive Traffic Signal System of Seoul, Korea.
13. Seoul Metropolitan Police Agency (2001) Specification of Traffic Signal Controller for the City of Seoul, National Police Agency, Korea.
14. Traffic Science Institute (1994) Comparative Analysis of Operational Performance in Different Shapes of Loop Detector Systems, Road Traffic Safety Association, Korea.