Effects of Loop Detector Installation on the Portland Cement Concrete Pavement Lifespan: Case Study on I-5

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Effects of Loop Detector Installation on the Portland Cement Concrete Pavement Lifespan: Case Study on I-5

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16. ABSTRACT

The installation of loop detectors in portland cement concrete pavement (PCCP) may shorten affected panel life, thus prematurely worsening the condition of the overall pavement. This study focuses on the performance of those loop embedded panels (LEP) by analyzing pavement data collected by WSDOT, and comparing it to the overall pavement performance on I-5 in King County. The results were divided by non-rehabilitated, diamond ground and dowel bar retrofit and diamond ground PCCP, as was done in the reference paper, to facilitate comparison. Overall, LEP perform worse – regarding panel cracking – in comparison to loop free panels (LFP), except on the small section of I-5 that has been Dowel Bar Retrofitted and Diamond grinded. For the non-rehabilitated PCCP, the difference between LEP and LFP with 1 crack is less than 1% but more than twice as many LEP have what is considered "failed" panels (2 or more cracks) than LFP. This might indicate that the loop installation affects more the severity of panel cracking than being the cause for it. Using these results and assuming panel replacement of the cost of $20,000 each, the cost of loop installation to the pavement was found to be $560 each. Traffic simulation was done for a section of I-5 to calculate delay due to lane closures, which loop detector installation constitutes. The user cost associated with the delay is a substantial part of the overall cost of loop installation, 40 – 60 percent depending on the number of affected lanes on the freeway. If user costs are accounted for, the overall cost of video and loop detection systems can be comparable.

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1 Introduction

The Portland cement concrete pavement (PCCP) on Interstate 5 was originally designed to last 20 years. Whether it is the mild climate of western Washington or the quality of aggregates used in the PCCP, the Portland cement concrete pavement in King County has now been in service for more than twice its design life, or over 40 years. But with average daily traffic of over 280,000, including 12,000 trucks and 50,000 daily transit trips, the pavement is deteriorating fast (Parametrix 2008). Panel cracking, corner breaking, faulting, patching and spalling are example of types of distress in the PCCP of I-5. Field study has concluded that the average increase in cracking on I-5 is about 6 percent per year, which indicates that the increase in cracking after 5 years will be at least 30 percent and at least 60 percent in 10 years. This would mean increasing number of multiple cracked panels and therefore increased need for complete slab replacement (Hansen et al. 2007).

There are over 800 loop detectors in the King County part of I-5, Milepost (MP) 139.9 – 177.7. The detectors measure occupancy and count the vehicles (and speed) as they drive over them. They give valuable data about traffic which can be used for many things, such as traffic forecasting, controlling traffic, online information about traffic and much more. The loop detectors are considered rather reliable and a cheap option to get this traffic data, but when they fail they are troublesome to repair, especially on a high volume interstate like I-5 because of the required lane closures.

There is a concern that the actual means of installation of loop detectors (sawcut into the concrete) may cause structural damage to those PCC pavement panels with

installed loop detectors. If this is the case, such structural damage would have to be included in the lifecycle cost of loop detectors and could cause the overall cost of loop detectors to rise dramatically perhaps making them less favorable traffic detection option. In addition, if the traffic impact during installation and maintenance of loop detectors are also taken into account the overall cost would likely rise further. Overall, inclusion of PCC pavement performance effects and traffic user costs may provide a better understanding of the true cost of loop detectors.

1.1 Research Objective

This study attempts to determine whether or not loop detector installation methods significantly affect long-term pavement performance. The area chosen for this study is Interstate 5 (I-5) in King County. It contains over 800 loop embedded PCC pavement panels. These loops may or may not be working and were installed using different methods at various times over the pavement's lifetime. This study will assess the condition of these loop embedded panels (LEP) and compare them to the overall pavement condition in the same area as reported in Hansen et al. (2007).

This will help better assess the true cost of inductive loop detectors (ILD) used to obtain traffic data. In general, the ILD is thought of as an accurate low-cost means to collect traffic data. However, if the real cost is higher than thought before because of added pavement distress, such general assumptions may not hold true. Additionally, if user delay costs during installation and maintenance of ILDs are accounted for then a more accurate life cycle cost for ILDs can be reported.

1.2 Organization

This report consists of six chapters:

- Chapter 2: an introduction to the basic concepts and tools used in this study
- Chapter 3: description of the study corridor and field data collected
- Chapter 4: research methods and data handling
- Chapter 5: data analysis and study findings
- Chapter 6: conclusions and recommendations

2 Background and Literature Review

In this chapter general information is provided on the principal concepts talked about later in the paper, such as the concrete pavement and the rehabilitation techniques that have been used in the study corridor, how and why the cracks come about and basic information about the simulation program VISSIM which was used for calculations. Detectors, both inductive loops and video detectors, are another part of the chapter, how they work and the installation process. In the end of the chapter there is a review on previous research, though papers focusing on loop embedded slabs could not be found. Thus the previous research chapter covers a study done on pavement condition of I-5.

2.1 PCC pavement general characteristics

The PCC pavement in the study area is jointed plain concrete pavement (JPCP) generally 9 inches thick placed on an unbound aggregate base of between 6 and 12 inches. Transverse joints are formed by sawcutting newly placed pavement at intervals (usually 15 ft intervals for the study area). Sawcutting is generally ¼ to ⅓ the depth of the PCC pavement thickness.

2.2 When should panels be replaced or reconstructed?

When cracking is so extensive that the panel is unable to effectively support traffic loads, panel replacement are often considered. When more than two cracks have formed in a panel, its capability to transfer loads is reduced and reconstruction or panel replacement should be considered (Hansen et al. 2007). To decide if a panel needs to be reconstructed or replaced depends on the number of panels in a given section that call for

actions to be taken. It is typically feasible to replace a panel if that number is below 10 percent of the total slabs in a section of pavement. If more than 10 percent of panels in a section are rated to be in need for replacement or reconstruction, then the section should be considered for reconstruction or some type of major rehabilitation (Muench et al. 2007).

2.3 Panel Replacement

If only a small amount of panels are severely damaged and in need of replacement in a section of pavement, it is possible to replace those panels selectively while maintaining the majority of pavement in place. This panel replacement is generally feasible of no more than 10 percent of the panels in a pavement section require replacement (Muench et al. 2007). Otherwise, it is likely more cost effectively to reconstruct the entire pavement. WSDOT estimates that the cost of full reconstruction of PCC pavement is upwards of $1.5 million per lane-mile. Other costs, such as of drainage, storm water treatment, safety improvements, capacity expansion, preliminary engineering, contingencies, and taxes can increase the cost to a total of $2 to $2.5 million per lane-mile depending upon location and market conditions. Panel replacements can vary in cost between about $2,500 per panel (for typical non-rapid replacement) up to about $25,000 per panel for rapid replacement in an urban freeway environment (Muench et al. 2007). A typical number reported by Muench et al. (2007) for rapid panel replacement is $20,000 per panel.

2.4 Linear Cracking in PCC Pavement

Over time, concrete slabs may crack linearly in response to stress, often referred to as “panel cracking" (Figure 1). When a panel cracks, it becomes less smooth resulting in rougher ride, water gets access to the base or/and sub-base and leads to erosion of the pavement support. Eventually the cracks will spall and disintegrate and the panel has to be replaced. The main causes of panel cracking, other than due to shrinkage and/or expansion, are wheel loads and repetition, panel curling due to differences in temperature between the top and bottom surfaces of a PCC slab, moisture stresses and lack of support from the base material for number of reasons. If saw cuts are assumed to have impact in panel cracking, the shape of the loops could be important.

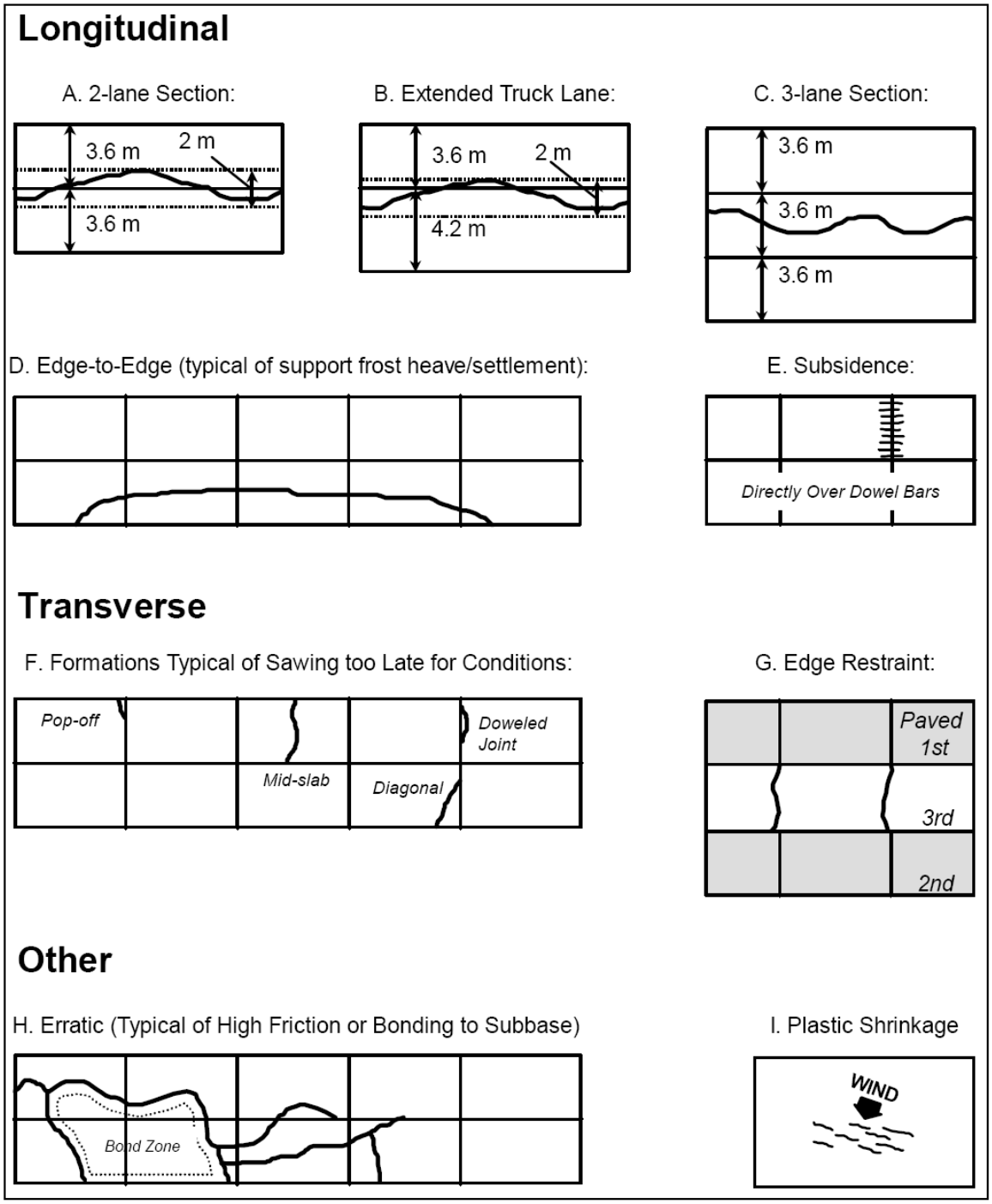

Figure 1. Typical crack formations (from Voigt 2002).

2.5 The VISSIM Simulation Program

VISSIM (software is developed by PTV AG of Karlsruhe, Germany) is a traffic micro-simulation tool that allows the user to graphically display complex traffic and report various traffic statistics based on the simulation (e.g., travel time, delay and queue lengths, number of stops, etc.). Current and future operations of every mode of transportation (i.e., general-purpose traffic, Heavy Goods Vehicle (HGV) (trucks), High Occupancy Vehicle (HOV), bus transit, light rail, heavy rail, rapid transit, cyclists and pedestrians) can be modeled in VISSIM. It is often used to analyze the traffic impacts of physical and operational alternatives before investment decisions are made. VISSIM is data intensive and has many features that can be adjusted. User must be experienced and the program must be calibrated to local conditions in order to get meaningful results.

2.6 Inductive Loop Detectors

Inductive Loop Detectors (ILD) has been the most popular form of traffic detection systems since the early 1960s. These detectors consist of copper wire, which is embedded in the pavement, connected to cabinets located beside the road. They are deployed about every half-mile on mainline lanes and ramps of freeways and state highways in the central Puget Sound region (Ishimaru and Hallenbeck 1999; Wang and Nihan 2004). The function of the ILD is that when a vehicle (or some other metal object) is on top of the loop, it causes inductance drop in the copper. Recorder monitors and counts the number of these inductance drops, which are then converted into vehicle counts. An ILD system is termed an “intrusive method” because it involves saw-cutting into the pavement’s surface.

There are a variety of loop shapes and sizes, but on freeways short loops, typically 6-ft x 6-ft, are used for detection. Wide (normally 6 ft in length and up to 46 ft for four lane approach) and long (often 6 ft wide and 20 – 80 ft long) loops are primarily used for presence detection, usually near an intersection. Figure 2 shows some common loop shapes used in practice.

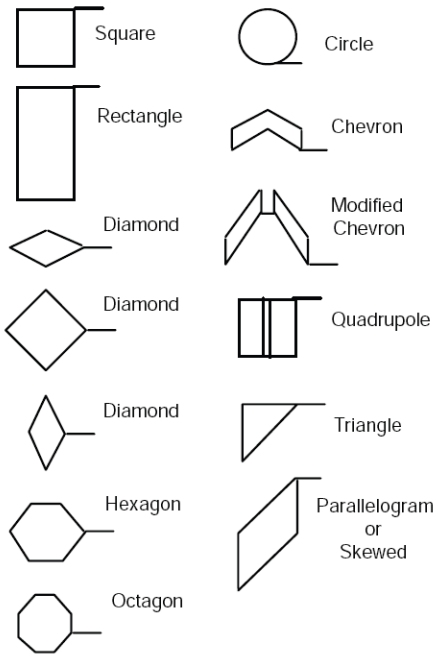

Figure 2. Small loop shapes (from USDOT 2006).

2.6.1 **ILD Installation**

The typical installation procedure involves a slot saw-cut into the pavement, 0.5 inch wide and 3 inches deep. After all cuts have been made, the slots are washed out to remove debris and vacuumed dry. Copper wire is then installed into the slot with a specified number of “turns” (iterations around the cut pattern (see Figure 3). The wire can then be encased in plastic sealant for protection. A lead-in wire runs from the wire

loop to a pull box beside the road. The pull box contains the connection between the lead-in wire and lead-in cable and provides access for maintenance. From the pull box a lead-in cable connects to the controller, and an electronics unit housed in the controller cabinet as shown in Figure 3.

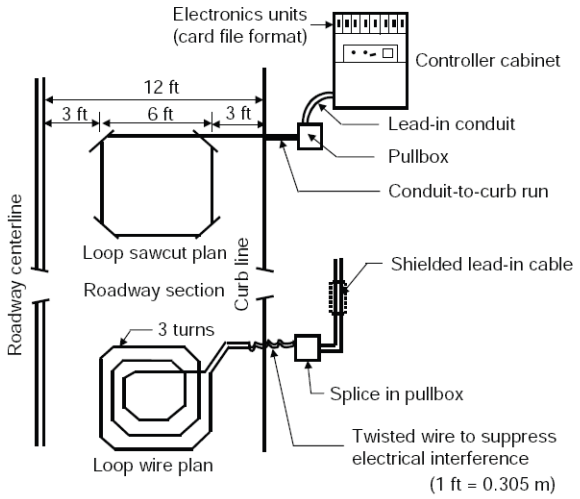

Figure 3. Inductive loop installation (from USDOT 2006).

The electronics unit supports functions such as selection of loop sensitivity and pulse or presence mode operation to detect vehicles that pass over the detection zone of the loop. After the wire has been installed a sealant is heated and pumped into the slot and after the sealant hardens the installation is complete. In terms of time, the saw cuts take about one hour per loop plus slot cleaning, wire installation and slot sealing. These activities may or may not be done in the same night. The overall time of installation can vary from 2 to 4 hours per loop detector (Dedinsky 2008). In the VISSIM simulation that

was produced for this study, 4 continuous hours of lane closures were assumed to be needed to install two loop detectors.

2.6.2 **ILD - Strength and Weaknesses**

The main strengths of ILDs compared to non intrusive detection methods such as video detectors is that they perform well in inclement weather conditions like rain, fog, and snow. ILDs are insensitive to poor lighting and also provide the best accuracy for count data when compared to other commonly used techniques (FHWA 2006). The major weaknesses of ILDs are that it requires a pavement cut, which requires lane closure and associated delay cost, and the wire loops are subjected to stresses of traffic and temperature. Table 1 summarizes the major strengths and weaknesses of ILDs.

Table 1. Strengths and Weaknesses of Inductive Loop Detectors (FHWA 2006)

Strengths	Weaknesses
• Flexible design to satisfy large variety of applications.	• Installation requires pavement cut
• Mature, well understood technology.	• Improper installation decreases pavement life.
• Large experience base.	• Installation and maintenance require lane closure.
• Provides basic traffic parameters (e.g., volume, presence, occupancy, speed, headway, and gap).	• Wire loops subject to stresses of traffic and temperature.
• Insensitive to inclement weather such as rain, fog, and snow.	• Multiple loops usually required to monitor a location.
• Provides best accuracy for count data as compared with other commonly used techniques.	• Detection accuracy may decrease when design requires detection of a large variety of vehicle classes.
• Common standard for obtaining accurate occupancy measurements.	
• High frequency excitation models provide classification data.	

Count, presence, speed and classification are the information that ILD can provide and the bandwidth needed to communicate the information is low to moderate. One of the main attractions to the ILD has been the material cost of the equipment needed for loop detector system, typically between $500 and $800 dollars (FHWA 2006).

2.7 Video Detectors

Video Image Processing (VIP) is another form of vehicle detection. Video detection system is known as a "non-intrusive" method of traffic detection because it does not involve installing any equipment directly into the road surface or roadbed. As vehicles pass the detectors (cameras), processors, fed by video from black-and-white or color cameras, analyze the changing characteristics of the video image. The cameras are usually placed on poles or structures above or on the side of the roadway. On freeways cameras are usually mounted on big traffic signs or on overhead bridges. When cameras are being installed or maintained, lanes sometimes have to be closed for a short while but not if the pole is on the side of the road or the cameras can be accessed from overhead bridges. Video detection systems require some initial configuration in order to register the baseline background image with the processor. This means inputting known measurements such as the distance between lane lines or the height of the camera above the roadway. Data gathered by the video detection system is typically lane-by-lane vehicle speeds, counts, and lane occupancy readings. More advanced systems provide additional data such as gap, headway, stopped-vehicle detection, and wrong-way vehicle alarms. Figure 4 shows mainline count and speed detection zones using a side-mounted camera. Count sensors are represented by the lines perpendicular to traffic flow and the speed sensors by the long, rectangular boxes.

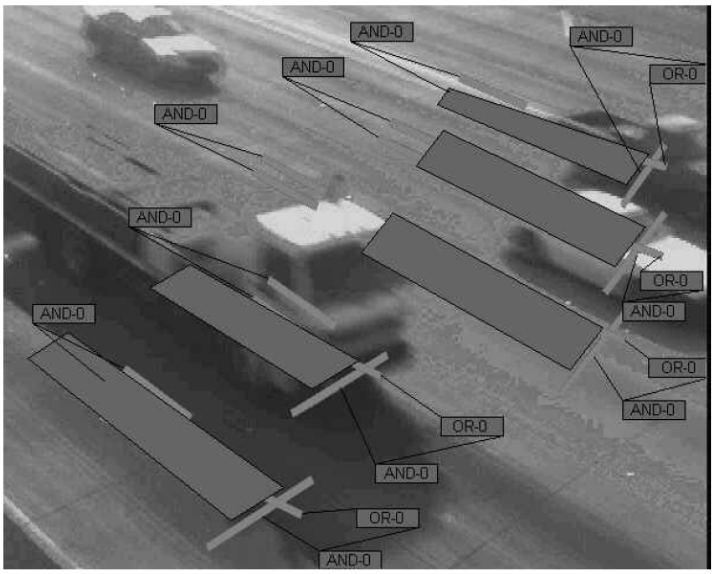

Figure 4. Video detection from a side-mounted camera (FHWA 2006).

2.7.1 **Video Detectors - Strength and Weaknesses**

Video detectors are advantageous because they can collect visual information as well as standard traffic data. Therefore, they can help operators observe traffic, identify incidents and monitor incident response. Conversely, visual information can be more easily disrupted by light, weather and shadows. Table 2 summarizes video detector strengths and weaknesses.

Table 2. Strengths and Weaknesses of Video Detection (FHWA 2006).

Strengths	Weaknesses
• Monitors multiple lanes and multiple detection zones/lane.	• Installation and maintenance, including periodic lens cleaning, require lane closure when camera is mounted over roadway (lane closure may not be required when camera is mounted at side of roadway)
• Easy to add and modify detection zones.	• Performance affected by inclement weather such as fog, rain, and snow; vehicle shadows; vehicle projection into adjacent lanes; occlusion; day-to-night transition; vehicle/road contrast; and water, salt grime, icicles, and cobwebs on camera lens.
• Rich array of data available.	• Reliable nighttime signal actuation requires street lighting
• Provides wide-area detection when information gathered at one camera location can be linked to another.	• Requires 30- to 50-ft (9- to 15-m) camera mounting height (in a side-mounting configuration) for optimum presence detection and speed measurement.
	• Some models susceptible to camera motion caused by strong winds or vibration of camera mounting structure.
	• Generally cost effective when many detection zones within the camera field of view or specialized data are required.

Video detector equipment costs are between $5,000 and $26,000 and the bandwidth needed for communication can be considered moderate to high, depending on how the data is transmitted (USDOT 2006).

2.8 Life Cycle Cost Analysis

Life cycle cost analysis (LCCA) is a procedure used to determine the overall cost of a project by considering both the present and future costs. All costs that may incur throughout the life of the project are considered and by doing that, a net present worth can be established. A net present worth is the cost after considering initial and future costs including inflation (Wilson and Falls 2003). The types of cost entered in the LCCA for a roadway construction over a given analysis period are:

- Initial construction cost
- Maintenance cost
- Rehabilitation cost
- Salvage cost (the asset value at the end of the analysis period)
- User delay costs

This study considers construction cost, user delay and pavement rehabilitation costs in an effort to estimate the life cycle cost of detector use. It does not consider maintenance costs or salvage value.

3 Study Corridor and Data

3.1 Study Corridor

Interstate 5 (I-5) is the major north-south highway facility in western Washington State. Average daily traffic (ADT) on I-5 in King County varies but is between about 130,000 and 260,000. Within King County, I-5 pavement is generally 9 inches of PCC pavement on Untreated Base (UB) that varies in thickness from about 0.59 to 1.08 ft. A number of sections in south Seattle use asphalt treated base (ATB) instead of UB and a few sections

near the northern King County boarder use a cement treated base (CTB) instead of UB. Most PCC pavement in King County was constructed between 1962 and 1971. Out of a total of 195.7 lane miles, I-5 in King County has 162.9 lane miles of non-rehabilitated PCCP, or 83 percent. It has now been in service for more than twice its design life and is showing significant distress (Hansen et al. 2007). Overall, Hansen et al. (2007) concluded that the majority of I-5 pavement in King County is in “poor” condition (using their definition) and that a good average number for the increase in panel cracking on I-5 in the King County area is about 6 percent per year. Table 3 summarizes this information.

Table 3. Pavement Structure by Section from WSPMS (from Hansen et al. 2007).

← N S →													
MILE POST NB	174.58 - 177.75	172.79 - 174.58	170.85 - 172.76	170.5 – 170.85	169.18 - 170.25	167.13 - 168.34	166.21 - 167.13	162.68 - 165.32	N/A	158.24 - 162.68	152.65 - 158.24	149.39 – 152.65	139.50 - 149.39
Mile Post SB	N/A	N/A	170.85 - 177.75	170.5 - 170.85	169.18 - 170.25	167.72 - 168.34	N/A	162.68 - 166.36	160.17 - 162.68	157.47 - 160.07	153.15 - 158.45	149.40 - 153.15	139.50 - 149.40
Year Constructed	1965	1965	1965	1963	1965	1964	1965	1967	1967	1967	1969	1966	1962
Number of Lanes	4	4	4	3	4	4	4	4	4	4	4	3	3
Thickness of ATB (ft)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.33	0.33	N/A	N/A
Thickness of CTB (ft)	0.17	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Thickness of UB (ft)	0.42	0.92	0.59	0.67	0.67	0.67	0.92	0.92	1.08	0.75	0.58	0.67	0.75

3.1.1 **Rehabilitation**

To date, mainly two methods of rehabilitation have been used on I-5 in King County: Diamond grinding was done in 1999 between mileposts 154.14 and 158.45, in both north- and southbound directions. There is total of about 27 lane miles of diamond ground PCCP on I-5 in King County, about 14% of the total lane miles. Diamond grinding was also done in 2009 on approximately 60 lane-miles in the greater Seattle area, however this was done after data collection for this study so its effects are not documented.

Two sections of the study corridor were reconstructed with dowel bar retrofit (DBR) and diamond ground PCCP in 2001. Southbound I-5 from milepost 144.45 to 146.18 and from milepost 147.67 to 149.69, total of 6.04 lane miles or about 3% of total lane miles in I-5 in King County. Figure 3.1 shows the study corridor and which sections have been reconstructed and which have not (Hansen et al. 2007).

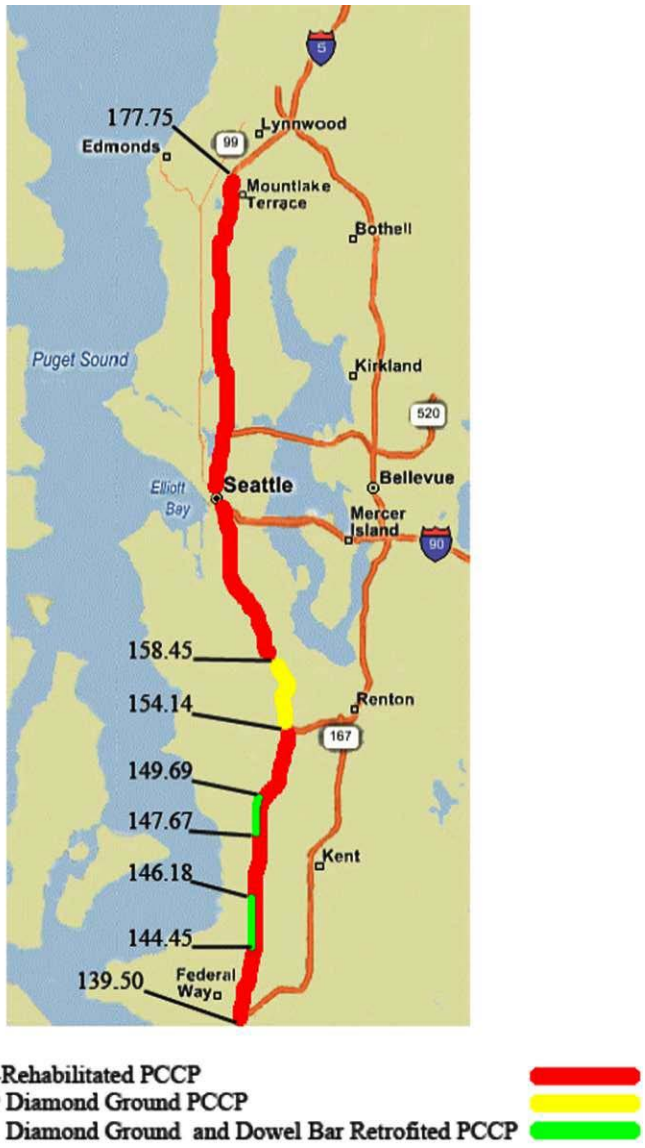

Figure 5. Rehabilitation of PCC pavement on I-5 in King County as of 2004 (from Hansen et al. 2007).

3.1.2 **Reconstruction**

In 2009 about 440 deteriorated concrete panels between the Boeing Access Road in South Seattle and the King/Snohomish County line and in the I-5 express lanes were replaced.

3.1.3 Loop installation

There are three types of loops embedded in the pavement of I-5 in King County: Circle loop, rectangular loop with softened corners and rectangular loops with sharp corners. The fourth category is a combination of those three loop types, e.g. when more than one loop detector is embedded in one concrete slab (Figure 6).

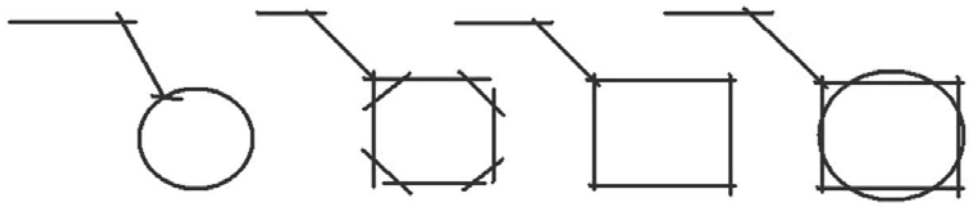

Figure 6. Types of loops: circle, rectangular with soft corners, rectangular with sharp corners and loop combo.

The oldest type is the rectangular one with sharp corner, first installed in the mid 1960's. Later it was realized that the sharp corners tended to rupture the loop detector wires and their use was largely discontinued. In the mid 1980's the first loops with softened corners were installed which solved somewhat the wire problem but increased the number of cuts in the pavement. Since the 1997 to 2000 time frame (the exact date is not known) only circle loops have been installed; these require only one cut and are considered the best for loop wire integrity. WSDOT estimates the lifespan of loop detectors to be about 8 – 12 years, but they do not keep records to document this (Dedinsky 2008). Other construction and maintenance activities can significantly decrease loop detector life span (Dedinsky 2008).

When a loop detector fails on the mainline of I-5 it is not repaired unless it can be done in conjunction with an existing construction project in the same area. When a non–

functioning loop detector is replaced by a new one, it is sometimes installed in the same panel as the broken one, creating additional sawcuts in that panel. Those kinds of panels are referred to as combo loop or loop combo in the rest of this report.

The cost of loop installation construction (not counting traffic control or materials cost) is estimated by the WSDOT to be about $1,000 (Dedinsky 2008).

3.1.4 **Simulation Study Corridor**

One section of I-5 in King County was selected to perform a traffic simulation in order to determine the traffic impacts of closing lanes specifically to install loop detectors. While this is not standard practice with WSDOT, it does represent the maximum potential user cost associated with loop detector installation. The selected section is a five mile stretch on southbound I-5 from the north border of King County (milepost 177.75) to NE 110th Street (milepost 172.86). This section was chosen because:

- The traffic condition in this part of I-5 is about average comparing to other parts of the study corridor; it experiences more traffic than the part south of Seattle and less than the part close to downtown Seattle.
- About half of the corridor has 4 lanes and the other 5 lanes (including HOV lanes) which allow simulations for both cases.
- There are no express lanes in this area. Express lanes would require additional simulation calibration.

3.2 Field Data – Pavement Cracking

3.2.1 **Data Collection**

The PCCP distress data used for this study was collected between July 8, 2004, and July 22, 2004 with the WSDOT distress collection van (Figure 7). Lanes 1 through 4, both north- and southbound directions, were driven between South- and North boundary of King County (milepost 139.5 to 177.75) and data collected. Data were filtered to remove pavement sections consisting of hot mix asphalt (HMA) surfacing and bridge decks. Data regarding slab cracking, transverse joint faulting and wheel path wear was gathered but only slab cracking data was used for this study since the main concern with loop detectors is their effect on slab cracking.

Figure 7. Pavement distress data collection van (Pathway 2008).

Images used for this study were collected from four cameras mounted on the WSDOT distress collection van (Figure 7). Two of the cameras face down and take continuous images of the pavement. These two images overlap to provide a complete image of the

pavement within the travelled lane. The other two cameras face forward and take images of the roadway ahead, giving information about the location and roadside inventory. These images are not taken as often as the pavement images; only one pair is taken for every five pairs of the downward-looking images (Hansen et al. 2007). Small errors in the data were detected, especially when there was a change in the number of lanes in the corridor. It was noticed that some parts of lanes were photographed twice and some not at all. When the van drove under an over head bridge, the images were dark and difficult to evaluate and also the first two images after the bridge were so bright that evaluation was problematic.

3.2.2 **Data Processing**

During the data collection process roughly 618,000 images were collected (e.g., Figure 8); 515,000 of which were downward-looking pavement images. The digital images of the pavement surface are displayed using Pathview II software. “Pathview II is a Windows 32-bit application which integrates all the pavement surface sensor data, digital images and location in a powerful and user-friendly system” (Pathway 2008). Each image shows about 1/8 – 1/6 of the length of a typical 15-ft long concrete slab, thus to view a whole slab 6 to 8 images have to be assembled (“stitched”) together.

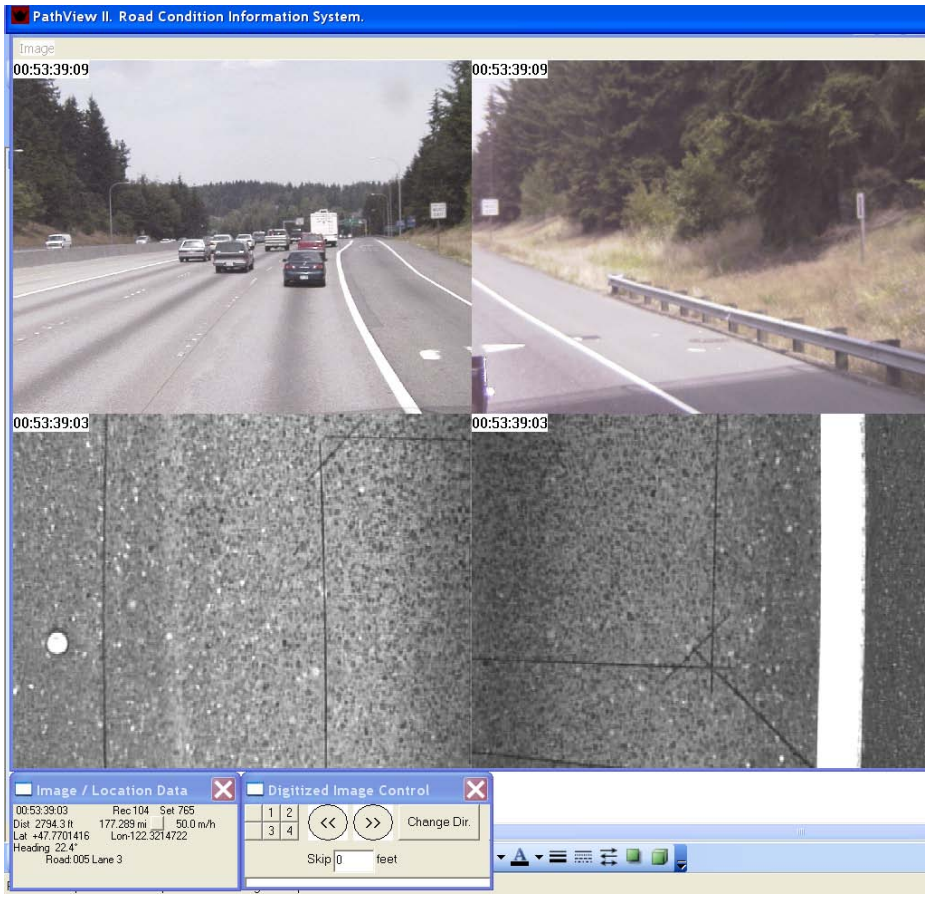

Figure 8. Pavement images displayed in Pathview II software.

Originally, the research plan was to view the images and grade the panels accordingly using the view shown in Figure 8, but the pavement images were often skewed and it was difficult to see whether a line was part of a loop detector or if it was a connection between a different loop and the cabinet. Also if a panel is cracked it can be difficult to decide if there are one, two or multiple cracks. To overcome these difficulties, the images that contained concrete panels with embedded loops were identified and assembled into larger aggregate images, each of which showed an entire loop embedded concrete panel (Figure 9). About 20% of this work had already been completed at the

start of this study. The remaining work, done as part of this study amounted to about 5,000 images assembled to show 803 different loop embedded concrete panels. Image overlap was not perfect so sometimes there are blank areas in the assembled concrete panel images.

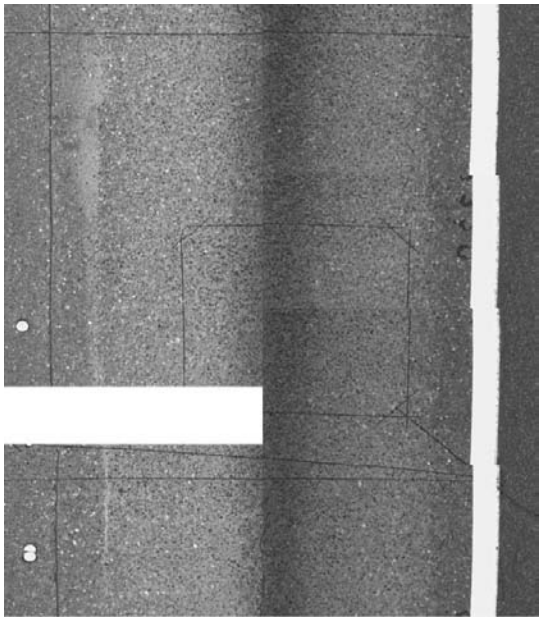

Figure 9. A whole concrete loop embedded panel assembled from 8 separate images.

3.2.3 Image labeling and information

Image numbers are displayed in the Image/location window (at the bottom left corner of Figure 8, enlarged in Figure 10). The file names are connected to numbers shown in the window: Set 765 means that the file is in folder 765 inside the database and the time which the data was collected, 00:53:39:03. The last digit can be 1, 2, 3, or 4 depending on from which camera the image is from. The total file name is a combination of these numbers: 765005339033.jpg.

Figure 10. Enlarged image of bottom left corner of Figure 8.

Other information used for the study were the milepost (177.289 in Figure 10), highway designation ("Road 005" in Figure 10) and lane ("Lane 3" in Figure 10). While WSDOT refers to the right-most lane as lane 1 and then increases lane numbers towards the center of the road, Pathview II does the opposite; referring to the left-most lane as lane 1 and increasing lane numbers towards the outside of the road. This can be confusing at times, however it is consistent. The Digitized Image Control window (Figure 10) is used to go to the next image, or a user-defined distance (in feet) can be entered in to skip images.

3.2.4 Finding Loop Detectors in Images

To find the images containing loop detectors, one lane of each direction was scanned and the loop locations documented. Loops in the other lanes were typically in the same location, but not always. WSDOT provided some information on loop locations but it was not comprehensive enough to be relied upon exclusively.

3.3 Field Data – Traffic

3.3.1 Data from Loop Detectors

Traffic data used for the simulation was obtained from WSDOT loop detection systems. The loops in the simulation corridor (milepost 177.75 to 172.86) were a combination of

square (6-ft by 6-ft), circle loops and combo loops. There were 11 mainline loop detection stations in the simulation corridor. Six of these were chosen to get lane-by-lane volume data. These six were chosen because they were generally equidistant from one another with about 20 city blocks between them and they also contained most of the on/off-ramp locations (Figure 11). Speed data and vehicle classification were attained by using dual loop detectors. There are four dual loop stations in the simulation corridor but only two were used: one in the middle of the simulation corridor (NE 145th street) and one in the end (NE 110th street). Dual-loop detectors are two consecutive single-loop detectors, placed about 16 feet apart. Time is measured from the time the first loop detects a vehicle until it is detected on the second one. The distance between the loops is known and therefore the vehicle speed can calculated. To determine the length of the detected vehicle, the calculated speed and occupancy is used.

Figure 11. Loop detectors used in the simulation corridor.

3.3.2 **Simulation - Time Period**

The selected simulation period was evenings (08:00:00 PM to 11:59:59 PM) of August 2006. Construction on freeways of the nature of a relatively simple loop detector placement typically takes place in the evening or at night, if possible, when the traffic volume is low. By doing this the impact from lane closures is minimized.

August was chosen because traffic volumes are generally lower then and the associated cost of delays are less resulting in a conservative estimate. The year 2006 was at last selected for it is fairly new data, so it demonstrates current traffic reasonable well, and it seemed to have more unfailing data than other years which were looked into. Data from all evenings in August 2006 were collected and imported to excel for analysis. Average evening traffic volume was calculated and no distinction was made between weekdays and weekends. These volumes, in 15 minutes (900 sec) intervals, were then put into the VISSIM 5.0 simulation program.

3.3.3 **Loop detector data background information**

Traffic Data Acquisition and Distribution (TDAD) was used to collect the data for the study. TDAD is a database which collects and stores the outputs of the Traffic Monitoring System (TMS) and makes them accessable via web-based query interface. Time, loop stations loop types (single or dual) can be specified and within each loop station, a particular loop can be selected. Once a query is submitted, a text file containing the requested data is generated for download. Tables 4 and 5 show example outputs from single and dual loops (UW 2007).

Table 4. Example of single loop data output from TDAD

SENSOR_ID	DATA_TIME	VOLUME	SCAN_COUNT	FLAG	LANE_COUNT	INCIDENT_DETECT
ES-167D:_MS___2	20060815200013000	10	189	0	1	0
ES-167D:_MS___2	20060815200033000	5	101	0	1	0
ES-167D:_MS___2	20060815200053000	5	106	0	1	0
ES-167D:_MS___2	20060815200113000	5	71	0	1	0

Table 5. Example of dual loop data output from TDAD

SENSOR_ID	DATA_TIME	SPEED	LENGTH	FLAGS1	FLAGS2	BIN1	BIN2	BIN3	BIN4
ES-167D:_MS__T1	20060815200013000	60.2	12.7	16	8	4	0	0	0
ES-167D:_MS__T1	20060815200033000	57.5	13.5	0	8	2	0	0	0
ES-167D:_MS__T1	20060815200053000	62	13	0	8	2	0	0	0
ES-167D:_MS__T1	20060815200113000	62	11	18	8	6	0	0	0

Information in Tables 4 and 5 are explained below (UW 2007).

- The first seven characters of the SENSOR_ID identify the cabinet name in which it is found. ES-167 refers to cabinet near 145th street and the last character can be either D or R, depending on if its a ramp-type cabinet (R), used for ramp metering, or freeway-type cabinet (D). The latter 7 characters describe the sensor, for example _MS___1 means mainline, South and lane one. The T indicates that this sensor is a dual loop sensor. Other characters are used to describe differnt attributes that the sensor has.
- DATA_TIME exhibits the time that the data was gathered, year, month, day, hour, minute and second are shown in sequence and the last three digits are always zero.

- VOLUME shows the number of vehicles that were sensed by the loop detector in the 20 second time period.
- SCAN_COUNT shows the number of times the loop is occupied within the 20-second interval. This scan is done 60 times per second so the maximum value of scan counts is 60 scans/second × 20 seconds = 1,200 scans per 20-second interval.
- FLAG is to show if the sensor is working properly, if the field contains the value 0 then the sensor is working correctly.
- LANE_COUNT and INCIDENT_DETECT were not used for this study.
- SPEED is the mean speed (mph) of all the vehicles detected in the 20 second interval.
- LENGTH shows the mean length (ft) of all the vehicles detected in the 20 second interval.
- Speed trap sensors are more complex than single loop sensors and apply a variety of checks on the reasonableness of their data. FLAGS1 and FLAGS2 represent those checks and show if the sensor is working correctly.
- BIN1 to BIN4 show the number of vehicles for each length. Below are the classifications used for TDAD:

BIN1 - passenger-cars	(0 ft to 19.9 ft)
BIN2 - single unit trucks	(20 ft to 39.9 ft)
BIN3 - double unit trucks	(40 ft to 71.9 ft)
BIN4 - triple unit trucks	(72 ft to 115 ft).

4 Methods

4.1 Pavement Distress Data Handling

The 803 different loop embedded concrete panels were viewed manually and the number of cracks seen was counted. This method is consistent with that used in Hansen et al. (2007). Each panel was annotated (0, 1, 2-3 or 4+) according to the number of cracks counted and type of loop was embedded in the panel (loop combos can be more difficult to classify: for the purposes of this study a panel is regarded as a loop combo if it has at least two loop embedded detectors). The four crack categories (0, 1, 2-3 and 4+) were used because they are the same as in Hansen et al. (2007) and therefore convenient for comparison. The results were gathered by lane and direction and the milepost for each panel was noted. Hence the cracked panel data could be presented by sections and categorized by rehabilitation technique used (if any). Examples of which cracks were counted and which were not are shown in Figures 12 and 13. In general, crack counting followed these rules:

- Deterioration other than linear cracks were not counted. This includes corner breaks, spalling and pop-outs.
- Crack severity was not accounted for. Thus, two panels that show the same number of cracks may not be in the same condition depending on crack severity. Typically, however, panel condition is closely related to the number of cracks with more cracks resulting in worse condition.
- The number of cracks in a patched panel was estimated based on cracks seen outside the patched area.

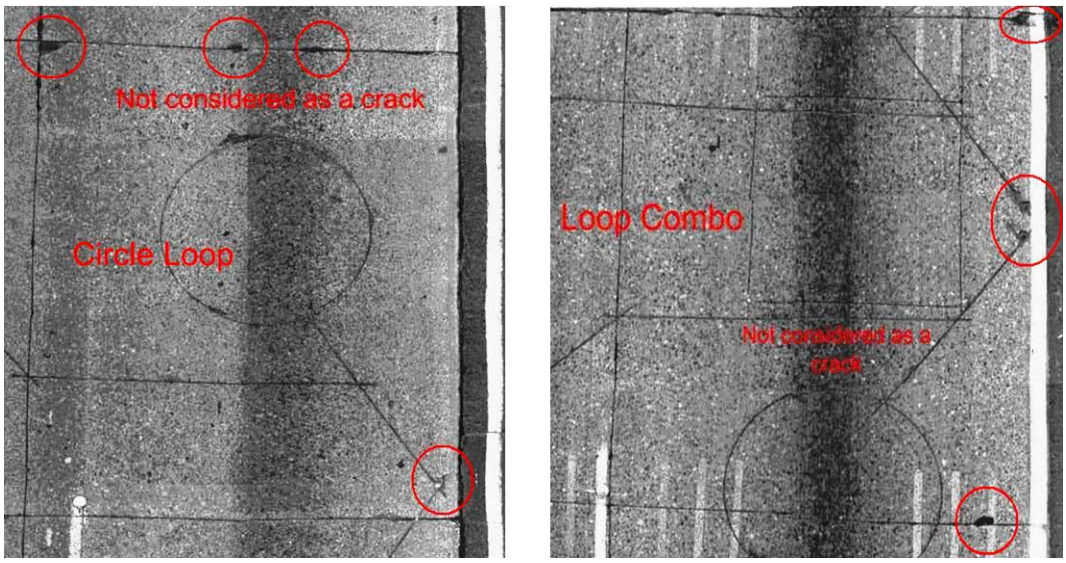

Figure 12. Example of analyzed panels: cracks that were not counted. No cracks were counted for either of these panels.

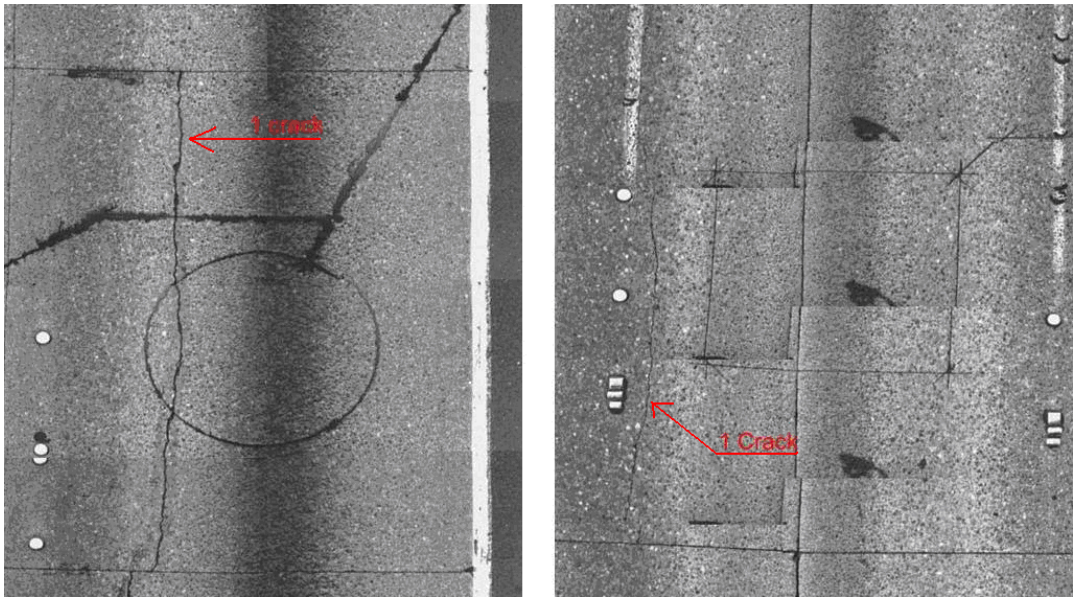

Figure 13. Example of analyzed panels: cracks that were counted. One crack for each of these panels was counted as annotated by the arrows.

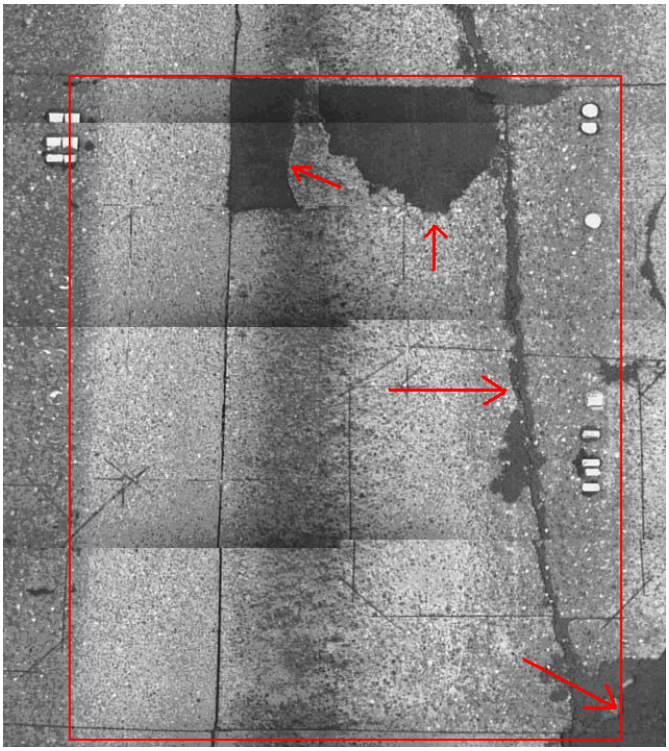

Figure 14. Example of analyzed panels: patched panel. Four cracks were counted for this panel as annotated by the arrows.

After grading each panel by lane, type and number of cracks, the results were converted into overall percent loop embedded panels (LEP) cracked and percent LEP cracked by the four categories of cracking, i.e. 0, 1, 2 – 3 or 4+ cracks.

4.2 Statistical Analysis

It was planned to statistically compare the results of this study's analysis the condition results of Hansen et al. (2007). However, several key factors led to the abandonment of a statistical analysis:

- The raw data of the reference paper was not accessible.

- The difference in sample sizes between the LEP and LFP is big, about 1 LEP to 100 LFP except for the dowel bar rehabilitation and diamond grinding section, where the ratio is 1 to 30.
- The sample sizes for the reference paper are not given. This required substantial assumptions to (1) estimate sample size simply by counting the number of lane-miles in each section, and (2) assume that the standard deviations for both data-sets are equal.
- The cracking data is not normally distributed making a comparison by t-test inappropriate.

While these issues could be overcome with effort, it was felt that the resulting statistics would be more representative of the assumptions made rather than the actual data. Therefore, statistical analysis was abandoned.

4.3 Traffic Data Handling

Vehicle data were aggregated into trucks and others. Trucks were assumed to be long vehicles and thus the number of trucks was determined by adding bins 2, 3 and 4.

4.4 Traffic Simulation

When all the traffic data had been gathered, the vehicle volumes were put into the VISSIM 5.0 simulation model together with the long vehicle percentage. Those volumes were assigned to the mainline as well as the off- and on-ramps. Data collection points were placed where the dual loops are located and then the model was calibrated with the speed- and volume data from the dual loop detector around NE 145th and NE 110th street. Data was not collected until after 15 min (900 sec) so the traffic was already

flowing in the whole corridor when the collection of data began. The volumes and the desired speed input were iterated multiple times in order to match actual data. Ten different random seeds were chosen for the multi-run simulation: 25, 28, 31, 34, 37, 40, 43, 46, 49 and 51. Random Seed initializes the random number generator and due to the stochastic nature of VISSIM's simulation model, several simulation runs with different random seeds are required to compute statistically reliable results (PTV 2008). Once calibrated against actual data (in terms of volume and speed) two simulations were ran: (1) near N 163rd street two lanes out of four were closed, and (2) near N 130th street two out of five lanes were closed. One travel time section was created for the whole corridor and delay and travel time data was attained with the lanes open and closed for comparison. After consulting with Martin Dedinsky, traffic engineer at WSDOT, the closure sections were decided to be 2000 ft and the closure duration was set at four continuous hours. Figure 15 shows a snap shot of a simulation run.

Figure 15. Snap shot of a simulation run.

The assumption was made that no rerouting or trip cancellation would take place, which is reasonable given the evening/night short duration closures simulated.

Based on travel time sections VISSIM generates delay data for networks. A delay segment is based on the travel time section. All vehicles that pass the travel time section are captured by the delay segment, independently of the vehicle classes selected in these travel time sections.

4.5 Delay Time and Cost from Simulation

For the VISSIM simulation program, a delay time measurement is defined as a "…combination of a single or several travel time measurements; regardless of the selected vehicle classes, all vehicles concerned by these travel time measurements are also regarded for delay time measurement. As delay segments are based on travel times

no additional definitions need to be done" (PTV 2007). A delay time measurement determines the mean time delay, compared to the ideal travel time (with no other vehicles and no signal control) calculated from all vehicles observed on a single or several link sections.

Travel time is explained in the VISSIM 5.0 user manual as: "Each (road) section consists of a start and a destination cross section. The average travel time (including waiting or dwell times) is determined as the time a vehicle crosses the first cross section to crossing the second cross section. During a simulation run, VISSIM can evaluate average travel times (smoothed) if travel time measurement sections have been defined in the network." Table 7 is an example of a compiled delay data file.

Table 6. Example of compiled data file for delay calculations

Time	Delay	Stopd	Stops	#Veh	Pers.	#Pers
VehC	All					
No.:	1	1	1	1	1	1
900						
14400	149.3	8.3	3.05	7798	149.3	7798
Total	149.3	8.3	3.05	7798	149.3	7798

Where:

- Delay: Average total delay per vehicle (in seconds). The total delay is computed for every vehicle completing the travel time section, which in this case was the whole simulation corridor, by subtracting the theoretical (ideal) travel time from the real travel time. The theoretical travel time is the time that would be reached

if there were no other vehicles and no signal controls or other stops in the network.

- Stopd: Average standstill time per vehicle (in seconds), not including passenger stop times at transit stops or in parking lots.
- Stops: Average number of stops per vehicle, not including stops at transit stops or in parking lots.
- #Veh: Vehicle throughput.
- Pers: Average total delay per person (in seconds), not including passenger stop times at transit stops. Not used for this study.
- #Pers: Person throughput. Not used for this study.
- VehC: Vehicle class. If needed vehicle classed (car truck etc.) can be excluded from the delay calculation.
- NO: Travel time section number. Only one section used in this simulation.
- 900 – 1400: Beginning and end time of data collection. Data collection began after 900 seconds of simulation so that the traffic was flowing all over the corridor.

When construction work-zone reduces the capacity or speed of a section of roadway, the users will experience longer travel times. These costs are not paid by the owner of the facility and thus called indirect costs, “paid” by the users in the form of additional time that the vehicle is in operation and the personal loss of time for the passengers. Since

user costs are not a direct cost, rather an indirect cost to society, they are often overlooked (Wilson and Falls 2003).

The delay cost can be calculated using equations like Caltrans uses:

$$UC = (\$/veh-hr)\left(\frac{L}{RS} - \frac{L}{IS}\right)(ADT)(PT)(CP) \tag{4-2}$$

Where

- UC = user delay costs due to construction
- $/vehicle-hour = average value of time due to delay. Typical values applied by Caltrans as of 2007 include: $10.46/hour for passenger cars and $27.38/hour for trucks
- L = project length (miles)
- RS = reduced speed through construction zone (mph)
- IS = initial speed prior to construction zone (mph)
- ADT = average daily traffic in current year
- PT = percent of the traffic that will be affected due to construction project
- CP = construction period (days)

In this study, a VISSIM simulation was done to estimate the user delay due to road closure for installation of the loop detectors. The simulation replaces the equations and other programs, and should be more accurate because it uses more and better traffic data and is calibrated. Table 8 shows WSDOT estimates the value of vehicle hours.

Table 7. Recommended Dollar Values per Vehicle Hour of Delay Adjusted to 2004 Dollars (WSDOT 2005).

Vehicle Class	Value per vehicle hour	
	Value	Range
Passenger Vehicles	$13.96	$12 to $16
Single-Unit Trucks	$22.34	$20 to $24
Combination Trucks	$26.89	$25 to $29

The delay data was not available for each vehicle type, so it is assumed that the delay affects all classes in the same way, i.e. the overall truck percentage in the corridor is used for single- unit trucks and combination trucks and no distinction made between them. The traffic data indicates that about 60% of the trucks are combination trucks and 40% single-unit. So the value per vehicle hour for the trucks is:

$$Truck(value/veh-hour) = \%Single-unit \times valueSingle-unit + \%Combin. \times valueCombin.$$

Or

$$Truck(value/veh-hour) = 40\% \times \$22.34 + 60\% \times 26.89 = \$25.07$$

5 Data Analysis and Findings

Results from the study are presented in this chapter. In the first two sub-chapters (5.1 and 5.2) the results are compared to the condition of the pavement in the whole corridor, obtained from the reference paper. The next three sub-chapters cover other results of the cracked (loop embedded) panel data, by type of loop, lane and direction. Finally, the cost of loop detectors are compared with that of video detectors.

5.1 Comparison – Cracked Panels with and without loops

Are loop embedded panels (LEP) in worse condition than other loop free panels (LFP)? In order to be consistent with the corridor condition assessment in Hansen et al. (2007) results are arranged by rehabilitation technique: non-rehabilitated, diamond ground and dowel bar retrofitted.

5.1.1 **Non-Rehabilitated PCCP**

Most of I-5 in King County was constructed in the 1960's and about 83% of it has still not been rehabilitated. In general, non-rehabilitated PCC pavements show signs of substantial wheel path wear from studded tires and contain an average of 29% faulted slabs (Hansen et al. 2007). Table 8 compares average cracking in non-rehabilitated pavement between all panels in I-5 in King County (data from Hansen et al. 2007) and the ones embedded with loop detectors (data from this study). Figure 16 shows this visually.

Table 8. Average Cracking for Non-Rehabilitated PCC Pavement.

Item	Non-Rehabilitated PCCP			
	All panels in the corridor (LFP)	# of samples	Loop embedded panels (LEP)	# of samples
NB Mile Posts	139.5 - 177.75 103.75 ln-mi	-	139.5 - 177.75 103.75 ln-mi	-
SB Mile Posts	139.75 - 177.75 59.05 ln-mi	-	139.75 - 177.75 59.05 ln-mi	-
No Cracks [%]	86.4	N/A	84.5	538
1 Crack [%]	11.2	N/A	10.4	66
2 - 3 Cracks [%]	2.1	N/A	3.6	23
4+ Cracks [%]	0.3	N/A	1.6	10
% PCCP Cracked	**13.6**	N/A	**15.5**	637

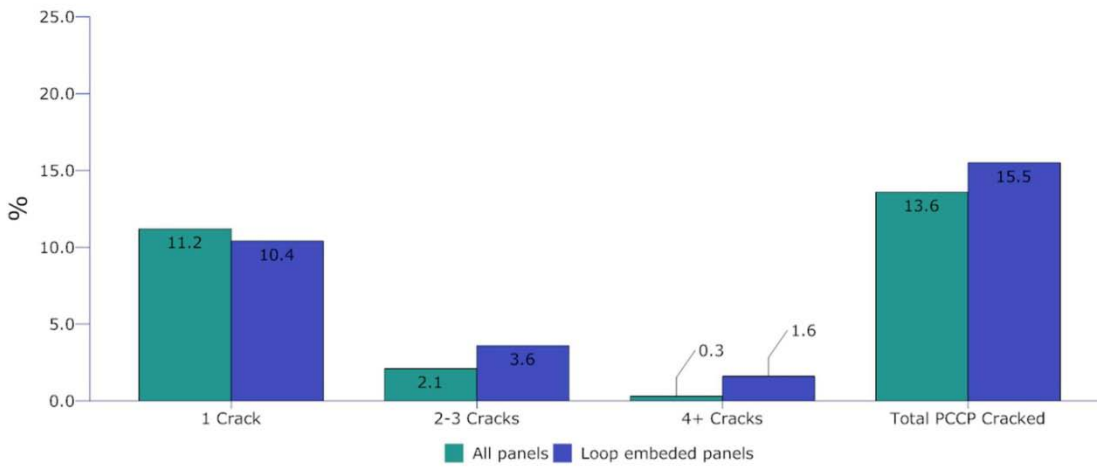

Figure 16. Average cracking for <u>non-rehabilitated</u> PCC pavement.

On average there is higher percentage of LEPs cracked than the LFPs. Results by number of cracks are:

- 1 crack: Slightly fewer LEPs with 1 crack as compared to LFPs.
- 2-3 cracks. LEPs have roughly 70% more cracked panels than LFPs.
- 4+ cracks. There are five times as many LEPs with 4 or more cracks than LFPs.

One possible explanation is that loops do not have much effect on the start of panel cracking but once a panel is cracked, some characteristic of the loop embedment hastens the deterioration process and the panel cracks more quickly.

5.1.2 **Diamond Ground PCCP**

At the time of this study (before the WSDOT Triage diamond grinding effort of 2009) WSDOT had reconstructed about 27 lane miles of I-5 in King County with diamond grinding. Table 9 compares average cracking in diamond ground pavement between all diamond ground panels in I-5 in King County (data from Hansen et al. 2007) and the ones embedded with loop detectors (data from this study). Figure 17 shows this visually.

Table 9. Average Cracking for <u>Diamond Ground</u> PCC Pavement

Item	Diamond Ground PCCP			
	All panels in the corridor (LFP)	# of samples	Loop embedded panels (LEP)	# of samples
NB Mile Posts	154.14 - 158.24 14.16 ln-mi	-	154.14 - 158.24 14.16 ln-mi	-
SB Mile Posts	154.16 - 154.4 12.68 ln-mi	-	154.16 - 154.4 12.68 ln-mi	-
No Cracks [%]	88.2	N/A	76.8	73
1 Crack [%]	10.7	N/A	15.8	15
2 - 3 Cracks [%]	1.0	N/A	7.4	7
4+ Cracks [%]	0.1	N/A	0.0	0
% PCCP Cracked	**11.9**	N/A	**23.2**	95

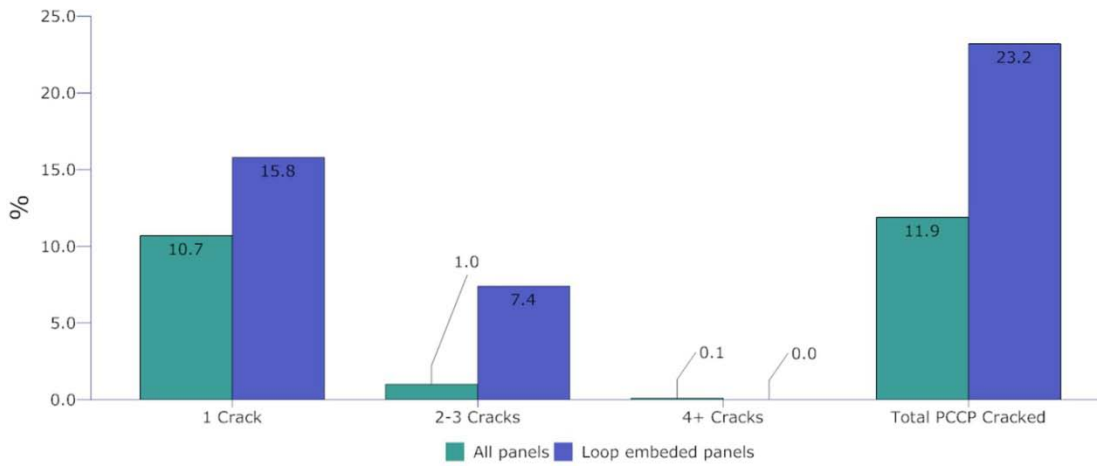

Figure 17. Average cracking for <u>diamond ground</u> PCC pavement.

On average there is higher percentage of LEPs cracked than the LFPs. Results by number of cracks are:

- 1 crack: The fraction of cracked panels is about 50% higher for LEPs than for LFPs.
- 2-3 cracks. There are seven times as many LEPs with 2-3 cracks than LFPs.

- 4+ cracks. There are no LEPs with 4 or more cracks and relatively few (0.1%) LFPs with 4 or more cracks. This is expected as diamond grinding operations often replace panels in poor condition.

The sample sizes behind some of those percentages are low, thus the significance of these results might not be as much as for non-reconstruction however the trends are similar.

5.1.3 **Dowel Bar Retrofit (DBR)**

At the time of this study, two sections (a total of 6.04 lane-miles) of the study corridor have been rehabilitated using a dowel bar retrofit (DBR). Table 10 compares average cracking in DBR between all diamond ground panels in I-5 in King County (data from Hansen et al. 2007) and the ones embedded with loop detectors (data from this study). Figure 18 shows this visually.

Table 10. Average Cracking for DBR PCC Pavement.

Item	Dowel Bar Retrofit and Diamond Grinded PCCP			
	All panels in the corridor (LFP)	# of samples	Loop embedded panels (LEP)	# of samples
NB Mile Posts	N/A	-	N/A	-
SB Mile Posts	144.45 - 149.69 6.04 ln-mi	-	144.45 - 149.69 6.04 ln-mi	-
No Cracks [%]	95.6	N/A	97.2	69
1 Crack [%]	4.0	N/A	2.8	2
2 - 3 Cracks [%]	0.4	N/A	0.0	0
4+ Cracks [%]	0.0	N/A	0.0	0
% PCCP Cracked	**4.4**	N/A	**2.8**	71
Average age of PCCP as of 2004	39.7	-	39.7	-

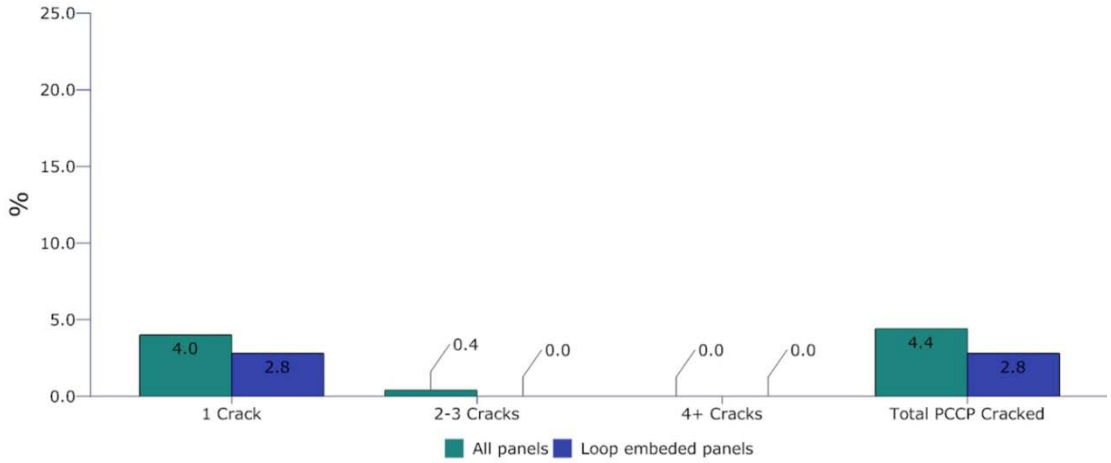

Figure 18. Average cracking for DBR PCC pavement.

On average there is lower percentage of LEPs cracked than the LFPs. Results by number of cracks are:

- 1 crack: The fraction of cracked panels is somewhat less than for LEPs than for LFPs.
- 2-3 cracks. There are no LEPs cracked.
- 4+ cracks. There are no LEPs or LFPs with 4 or more cracks and relatively few (0.1%) LFPs with 4 or more cracks. This is expected as DBR operations often replace panels in poor condition.

The sample sizes behind some of those percentages are low and some previously cracked panels were replaced in the DBR process, thus these results may be insignificant.

5.2 Comparison – by sections

In Hansen et al. (2007) the Washington State Pavement Management System (WSPMS) was used to identify sections by their year of construction and the type and thickness of base layers. Thirteen different sections of construction were identified. The results from

this study were configured in the same way so the sections could be compared. The construction years and type and thicknesses of the base layers are displayed in Table 3 in Chapter 3. Table 11 compares LEPs and LFPs by section.

Table 11. Comparing LEPs and LFPs by Section

← N S →													
MILE POST NB	174.58-177.75	172.79-174.58	170.85-172.76	170.5 – 170.85	169.18-170.25	167.13-168.34	166.21-167.13	162.68-165.32	N/A	158.24-162.68	152.65-158.24	149.39-152.65	139.50-149.39
Mile Post SB	N/A	N/A	170.85-177.75	170.5 – 170.85	169.18-170.25	167.72-168.34	N/A	162.68-166.36	160.17-162.68	157.47-160.07	153.15-158.45	149.40-153.15	139.50-149.40
% of Cracked panels (all panels)	17.4	17.7	20.0	16.3	11.1	11.3	4.4	15.6	13.8	8.5	18.5	17.7	5.5
% of Cracked LEP	19.6	34.4	19.6	7.1	10.0	18.5	0.0	27.8	26.7	17.6	19.0	10.0	5.5
Sample size of LEP	56	32	92	14	30	27	14	36	30	108	126	40	200

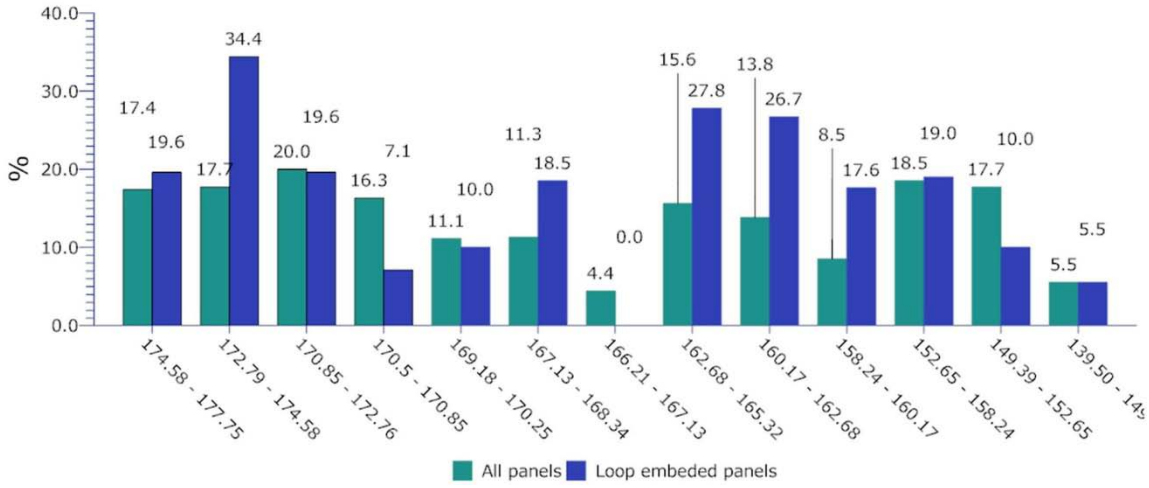

Figure 19. Comparing LEPs and LFPs by section.

The sections vary in length, the longest section is about 10 miles and the shortest less than a mile, so the number of panels (sample sizes) in each section are different. The LEPs have higher percentage of cracking in 7 of the 13 sections. In three sections the LFPs have higher percentage of cracking. It seems that LEPs perform worse compared to LFPs from mileposts 158 – 165; the section around and north of King County Airport (Boeing Field). No apparent correlations exist between cracking and any data contained in Table 3 (construction year, number of lanes, base type, base thickness).

5.3 Results – by type of loop

There are three types of loops in the study corridor, circle loops, rectangle loops with soft corners and rectangle loops with sharp corners. In some places in the corridor two or more loops have been installed in the same panel (called a “loop combo” in this report). The trend has been to soften the corner of the slots and since 1997 WSDOT only installs circle loops on the freeway. The main reason for this is that the sharp corners can damage the chopper wire in the loop detector, making it useless. Other reason is that it is

known that sharp corners in concrete create stresses and therefore it is more likely to crack. The number of cracks by loop type is shown in Table 12 and Figure 20.

Table 12. Number of Cracks in LEPs by Type of Loop Detector

Item	Circle loops	Rectangle loops Soft corners	Rectangle loops sharp corners	Loop Combo	All types of loops
No Cracks	92.0	81.0	81.8	92.3	84.8
1 Crack	7.4	10.5	13.4	3.1	10.3
2 - 3 Cracks	0.5	6.3	3.8	1.5	3.6
4+ Cracks	0.0	2.1	1.0	3.1	1.2
% PCCP Cracked	8.0	19.0	18.2	7.7	15.2
First installed	1997 - 2000	Mid 80's	Mid 60's	N/A	N/A
# of samples	188	237	313	65	803

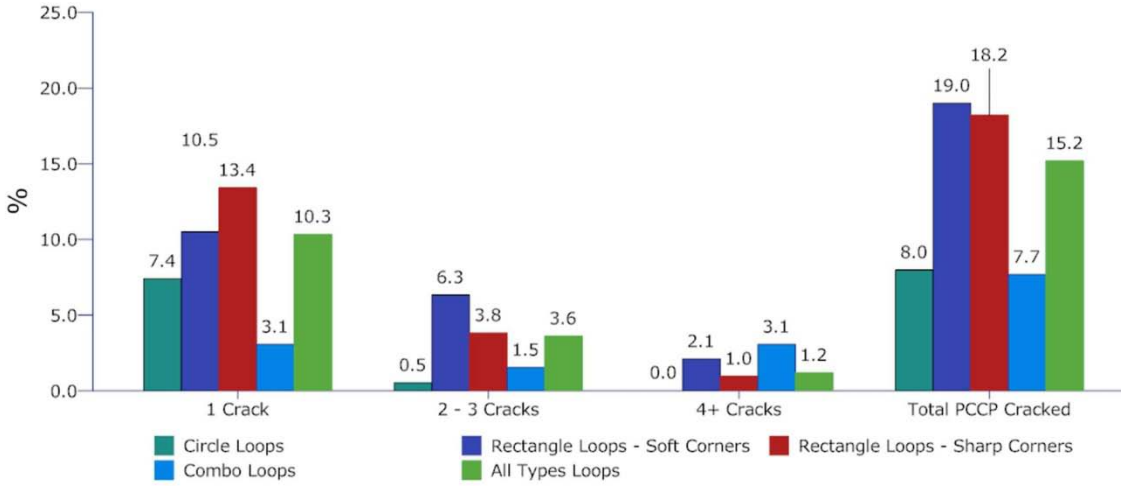

Figure 20. Number of cracks in LEPs by type of loop detector.

There is a significant confounding effect that makes direct comparison by loop type difficult: loop type is highly correlated with the age of a loop (e.g., circle loops were installed most recently so are younger than rectangle loops, etc.). Thus, of the three types of loops the circle loop performs best as would be expected since they were installed

fairly recently. Surprisingly, the soft corner rectangle loops exhibit more overall cracking than the sharp corner rectangle loop even though they were installed on average 20 years later. Explanations for this could be: (1) it is better to saw-cut the pavement when it is new than is to do it many years after construction, or (2) the soft corner rectangular loop installations were not done correctly (e.g., saw cuts too deep). Another rather unexpected result is that the panels with loop combo (2 or more loops) perform overall very well, even better than the circle type. The reason for this could be that the location of a new cut is not random (i.e., a LEP is not cut again if it is already cracked. However, the severity of cracked loop combo panels is high (they have the highest percentage of 4+ cracks). This could mean that when a panel with a loop combo cracks, panel deterioration occurs more rapidly than other types. It is difficult to assign cause to the types of loop cuts in loop combo panels since combinations vary greatly.

5.4 Results – by lane

Most of I-5 in King County has 4 lanes in each direction. It is interesting to see how the panel cracking varies by lane.

Table 13. Percentage of Cracked LEPs by Lane and Rehabilitation Type.

	Non-Rehabilitated PCCP		Diamond Ground PCCP		Dowel Bar Retrofit and Diamond Grinded PCCP		Total – With and without Rehabilitation	
	% Cracked LEP	Samples	% Cracked LEP	Samples	% Cracked LEP	Samples	% Cracked LEP	Samples
Lane 1	16.3	123	34.8	23	0.0	18	16.5	164
Lane 2	18.9	159	31.8	22	5.9	17	19.2	198
Lane 3	15.1	179	24.0	25	5.6	18	15.3	222
Lane 4	12.5	176	4.0	25	0.0	18	10.5	219

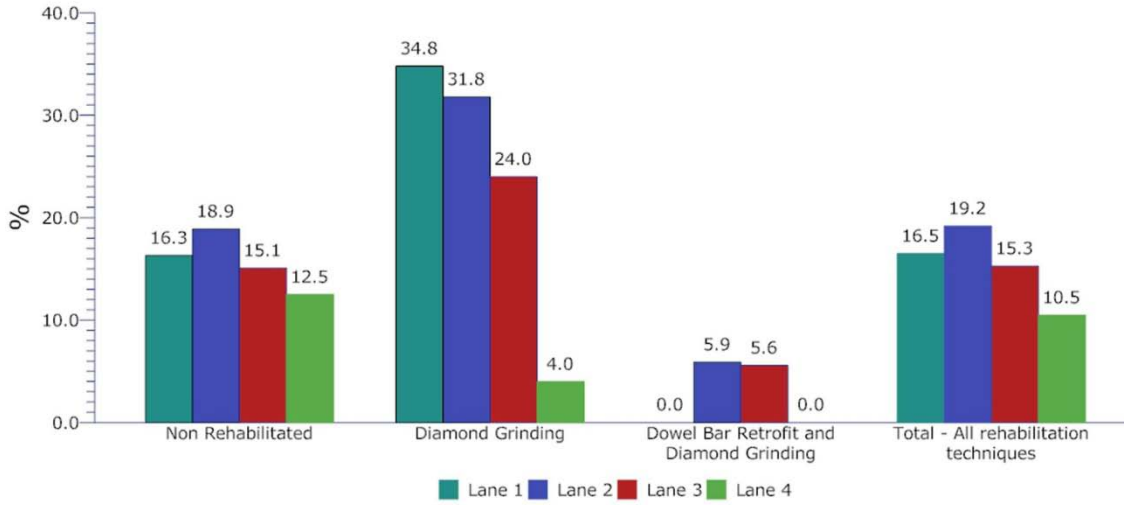

Figure 21. Percentage of cracked LEPs by lane and rehabilitation type.

It is hypothesized that lanes with the highest truck traffic (including buses) will have a higher fraction of LEPs with cracks. To test this hypothesis, a small sample of truck traffic by lane was taken on southbound I-5 at NE 145th Street and NE 110th Street. On these locations there are 4 and 5 lanes respectively. The sample was taken in August 2006 and contained 4 hours of average evening (8:00 pm – 12:00 am), 4 hours of average weekday (Monday – Wednesday from 6:00 am to 12:00 pm) and 4 hours of average weekend (Saturday and Sunday 12:00 pm – 16:00 pm) traffic. Traffic volume was not taken into account, just the ratio between small vehicles and trucks (including buses) and simple averages were taken from these three time periods and the results are shown in Table 14.

Table 14. Percent Truck Traffic by Lane

	145th Average (4 lanes)	110th Average (5 lanes)
	% Trucks	% Trucks
Lane 1	4.0	2.6
Lane 2	8.9	5.9
Lane 3	2.4	8.6
Lane 4	3.5	3.3
Lane 5	N/A	3.3

LEP cracking tracks with truck traffic reasonably well with Lane 2 having the highest truck traffic and highest percentage of cracked LEPs. Other confounding elements are: (1) if lane 4 is an HOV lane it may have been constructed more recently, and (2) trucks tend to avoid drop lanes and off-ramp cues. As stated the diamond ground LEPs show big percentages of cracking.

Table 15 and Figure 22 show the number of cracks by lane without regard to rehabilitation method.

Table 15. Number of Cracks by Lane

	1 Crack		2 - 3 Cracks		4+ Cracks	
	%	samples	%	samples	%	samples
Lane 1	10.4	17	5.5	9	0.6	1
Lane 2	15.7	31	2.5	5	1.0	2
Lane 3	10.4	23	4.1	9	0.9	2
Lane 4	5.5	12	2.7	6	2.3	5

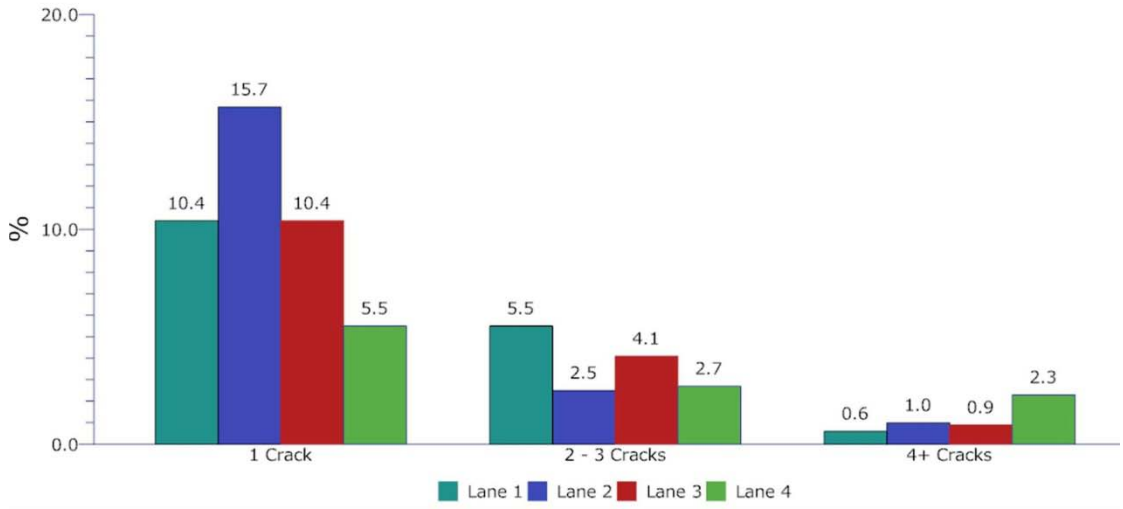

Figure 22. Number of cracks by lane.

The results for 1 crack per panel is very similar to the overall percentage of cracked panels but for 2-3 cracks there is a spike in lane 3 which might not be expected. The most unexpected result is in 4+ cracks, lane 4 has the highest percentage of 4 or more cracks per panel. If sample size were increased (here the sample size is low) it is unknown if this trend would still be prevalent.

5.5 Results – by direction

It is interesting to see if either the northbound or southbound direction is in worse shape than the other. Differences may indicate trends in truck loading (e.g., more empty trucks in one direction and more loaded trucks in the other). Table 16 and Figure 23 show cracked LEPs for northbound and southbound directions by lane.

Table 16. Cracked LEPs by Lane and Direction

	With and without rehabilitation			
	NB % of cracked LEP	NB # of LEP	SB % of cracked LEP	SB # of LEP
Lane 1	20.0	90	12.2	74
Lane 2	25.3	95	13.6	103
Lane 3	19.4	108	11.4	114
Lane 4	8.4	107	12.5	112
All lanes	18.0	400	12.4	403

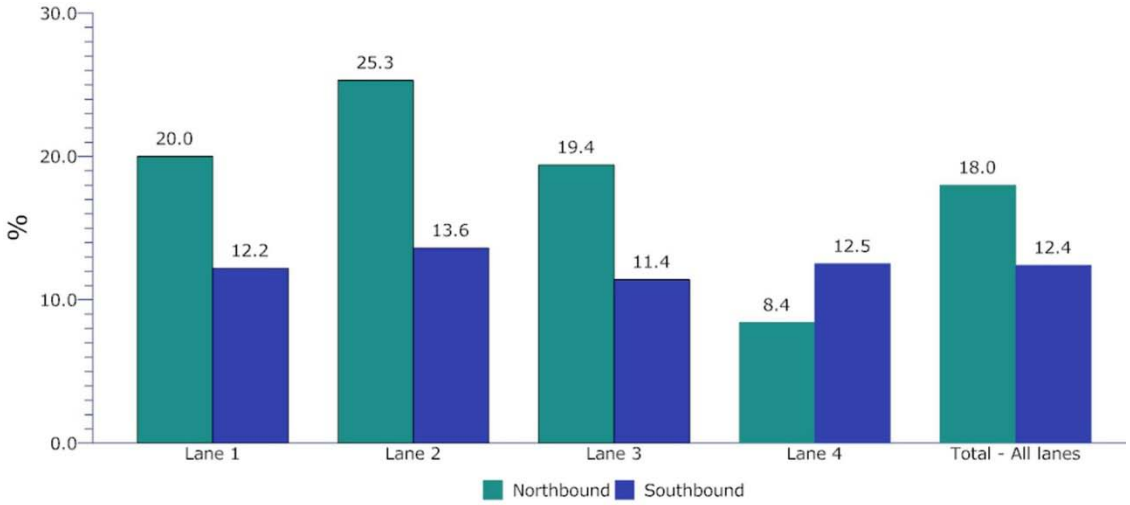

Figure 23. Cracked LEPs by lane and direction.

With the exception of lane 4, the northbound direction is in significantly worse shape than the southbound. One hypothesis to explain these results is that truck traffic in the northbound direction is higher. To test this hypothesis, a small sample of truck traffic by direction was taken on northbound and southbound I-5 at NE 145th Street. There are five lanes on this location in the northbound direction compared to four in the southbound direction. As with the previous truck sample, the sample was taken in August 2006 and contained 4 hours of average evening (8:00 pm – 12:00 am), 4 hours of average weekday

(Monday – Wednesday from 6:00 am to 12:00 pm) and 4 hours of average weekend (Saturday and Sunday 12:00 pm – 16:00 pm) traffic. Traffic volume was not taken into account, just the ratio between small vehicles and trucks (including buses). Results show there were 9.4% trucks in the northbound direction compared to 5.3% trucks for the southbound direction for the sample times. This gives some indication that there may be more truck traffic in the northbound direction, which the LEP cracking data seems to indicate. It is difficult to determine whether or not data from Hansen et al. (2007) (Table 17) for LFPs corroborates these findings. While LFP cracking appears to be slightly worse in the southbound direction, the significance of this is not known.

Table 17. Percentage of I-5 where LFPs are Cracked in Excess of 10% (from Hansen et al. 2007)

Lane/Direction	Northbound [10% of LFP Cracked]	Southbound [10% of LFP Cracked]
Lane 1	35.54	43.19
Lane 2	51.39	58.86
Lane 3	44.32	29.71
Lane 4	14.87	19.31
Total	36.28	37.28

5.6 Cost – Inductive Loop Detectors and Video Detectors

5.6.1 **Cost due to faster deterioration**

The results in Chapter 5 indicate that LEPs may be in worse condition than comparable LFPs. In Hansen et al. (2007) a panel cracking rate of 5 or 10 percent over a geographic section is used to designated a section as “failed” and in need of rehabilitation or replacement. For LEPs there are no geographic sections of continuous panels (typically they occur as just one or two in a row) so estimation of percent of cracked panels in a

section is not possible. Therefore, the definition of “failure” for a LEP is a panel that has two or more cracks. To evaluate the cost to pavement when installing a loop detector, it is considered most reasonable to look at non-rehabilitated pavement only and not the sections with diamond ground and dowel bar retrofit because those rehabilitations were done only recently, and enough experience has not been gained to evaluate the pavements lifespan of those sections for the overall cost due to cracked panels. Calculations for the increased pavement cost due to loop installations are shown in Table 19.

Table 18. Calculations Increased Pavement Costs due to Loop Installations

	2+ cracks [%]	# of LEP [Non-rehab]	Cost of panel replacement [$]	# of panels to be replaced	Cost per LEP [$]
Loop Embedded Panels (LEP)	5.2	637	20,000	33	1040
Loop Free Panels (LFP)	2.4	637	20,000	15	480
Difference	2.8	-	-	18	560

Calculation method: The percentages of panels with two or more cracks were calculated and the difference between LEP and LFP found. Then that number was multiplied by the number of LEP and that gave a theoretical number of additional panels that would have to be replaced because of loop installation. To find cost the panel replacement cost is multiplied by the number of extra panels that is needed to replace and to get the cost for each LEP or each loop that number was divided by the total number of LEPs.

Calculation:

$5.2\% - 2.4\% = 2.8\%$ more LEP with 2+ cracks than LFP

$2.8\% \times 637 = 18$ more panels cracked due to loop installation

$18 \times \$20{,}000 / 637 = \$560$ the extra cost due to loop installation

5.6.2 User Cost due to Loop installations

To calculate the user cost (cost of delay) of installing loop detectors, two lanes (or three when there were 5 lanes) at a time were closed in the simulation program. First the delay was obtained from the program with all lanes open and then with the designated number of lanes closed. It was assumed that two lanes would remain open at all times. This resulted in first closing lanes 1 and 2 and then lanes 3 and 4. For the location that had 5 lanes, lanes 1 and 2 were closed and then lanes 3, 4 and 5. Table 20 and 21 show the results.

Table 19. Lane Closure Results for 4 Lanes

	Delay [sec]	Stopd [sec]	Stops [number of]	average travel time [sec]	#Veh	Total Delay [Veh-hour]
Lane 1 and 2 closed	148.4	9.1	3.1	383.0	7850	323.5
Lane 3 and 4 closed	294.1	22.3	7.2	528.9	7980	652.0
Average from the two cloures	221.3	15.7	5.2	455.9	7915	486.4
All lanes open	8.9	0.00	0.0	243.1	8668	21.3
Difference	212.4	15.7	5.2	212.8	-753	465.1

Table 20. Lane Closure Results for 5 Lanes

	Delay [sec]	Stopd [sec]	Stops [number of]	average travel time [sec]	#Veh	Total Delay [Veh-hour]
Lane 1 and 2 closed	12.1	0.0	0.0	246.5	8567	28.8
Lane 3, 4 and 5 closed	206.8	16.4	4.8	442.4	7089	407.2
Average	109.4	8.2	2.4	344.4	7828	238.0
All lanes open	8.9	0.0	0.0	243.1	8668	21.3
Difference	100.5	8.2	2.4	101.3	-840	216.7

Lane Closure Results for 4 Lanes Comments. The delay is significantly higher when lanes 3 and 4 were closed compared with when lanes 1 and 2 were closed, because of off-ramp traffic that interrupted the mainline flow. Average delay for a two lane closure is 221.3 sec/veh. The number of vehicle throughput is not the same because when vehicles are stopped for more than 7 seconds they diffuse. This number can be changed and 7 seconds were said to be reasonable (Zhang 2008). The difference in delay in veh-hour is the difference between average delay for two lane closure and when all lanes are open. This number describes the delay due to the lane closures.

Lane Closure Results for 5 Lanes Comments. When two out of five lanes of the freeway are closed, the delay does not increase that much, only about 3 sec/veh, but when three lanes were closed the increase in delay rose nearly 200 sec/veh from when no lanes were closed.

The cost of each vehicle-hour is estimated by WSDOT to be $13.96 for cars and after some calculations (shown in Chapter 4.2.6) the average cost of trucks were found to be $25.07. Trucks, or long vehicles, were calculated to be around 5% of the total traffic. Tables 21 and 22 show the cost of delay due to lane closures.

Table 21. User Cost for 4 Lane Freeway due to Loop Installations

	Ratio in traffic	Delay [veh-hour]	Cost per veh-hour	Cost	Cost per loop
Car	0.95	465.1	$13.96	$6168	$3084
Truck	0.05	465.1	$25.07	$583	$292
Total	1	-	-	$6751	$3376

Table 22. User Cost for 5 Lane Freeway due to Loop Installations

	Ratio in traffic	Delay [veh-hour]	Cost per veh-hour	Cost	Cost per loop
Car	0.95	216.7	$13.96	$2874	$1150
Truck	0.05	216.7	$25.07	$272	$109
Total	1	-	-	$3146	$1258

Assuming that I-5 would be closed to install or replace a loop detector, the user cost would be about $3,400 for the 4 lane sections and $1,300 for 5 lane sections. These are theoretical results because WSDOT does not close lanes solely to install or replace loop detector, but waits for other projects that have to be done on the freeway, and installs the loops simultaneously.

5.6.3 Video Detectors

When estimating the cost of video detector installation it is assumed that no lane closures have to be made, and therefore no user cost associated with it. The installation cost without the equipment needed is considered to be 30% of the loop installation cost, about $300. WSDOT did not have an estimation for this cost item, so this is a rough estimate made by the author, based on how much work seems to be affiliated, in proportion to the loop installation.

5.6.4 Cost Comparison – Inductive Loop Detectors and Video Detectors

Table 23 shows a comparison between the theoretical costs of loop detection and video detection assuming maintenance costs are minimal. The average lifetime of loop and video detector is assumed to be the same based on WSDOT advice (Didensky 2008).

Table 23. The Cost of Installing Loop Detectors and Video Detectors

	Inductive Loop Detector	Video Detector
Equipment cost [$]	500 - 800	5,000 - 26,000
Installation Cost [$]	1,000	300
Cost on the Pavement [$]	560	-
User cost [$]	1,260 - 3,380	-
Total Cost [$]	3,320 - 5,740	5,300 - 26,300

For the loop detectors the user cost is a substantial part of the total cost of loop installation (about 60% in a four lane freeway and 40% in a five lane freeway). If this cost is accounted for, a video detector installation may actually result in a lower lifecycle cost on a 4 lane freeway.

6 Conclusions and Recommendations

6.1 Conclusions

This study focused on PCC pavement panels with embedded traffic loop detectors (LEPs) on I-5 in King County and how they are performing in relation to other panels (i.e., loop free panels, LFPs). Major findings were as follows:

- **Results may not be transferrable**. Since there are few (if any) studies on LEP condition it was not possible to verify results of this study with others. It may be that different study corridors show different results.
- **Comparison by cracking**. LEPs show poorer performance than LFPs in terms of cracking except on the small section of I-5 that has been dowel bar retrofitted and diamond ground.
    - Non-rehabilitated PCC pavement. For panels with one crack, the difference is not much (1 – 2%). However, when considering "failed panels" (defined as those with 2 or more cracks) the difference between LEP and LFP is substantial: the fraction of LEPs is twice as high as the fraction of LFPs. have 2 or more cracks - percent vise – than LFP. This might indicate that the loop installation tends to influence the *severity* of panel cracking rather than the *initiation*.
    - Diamond ground PCC pavement. The LEP are in worse condition than LFP in all categories. Specifically, the fraction of "failed" LEPs (2 or more cracks) is about seven times the fraction of "failed" LFPs (2 or more cracks).

- Dowel bar retrofit (DBR) PCC pavement. There are no "failed" (2 or more cracks) LEPs in the DBR section and only 0.4% of LFPs are "failed" (2 or more cracks). This is expected since failed panels are usually removed and replaced in the DBR process.

- **Comparison by section (see Table 3 for section definition)**. LEPs have higher cracked panel fraction in 7 of the 13 sections. In three sections the LFPs have higher cracked panel fraction (two of these have low samples sizes making the results less certain). It is difficult to draw any firm conclusions on a section-by-section basis although it does seem that LEPs perform worse than LFPs from mileposts 158 – 165 (near and north of Boeing Field).
- **Comparison by loop type**. LEPs with circle loops have fewer cracks than those with rectangular loops. This effect is pronounced in panels with two or more cracks. This may not be a reasonable comparison because circle loops were installed much later than the rectangular ones.
- **Cost attributable to shorter panel life from loop detector installation**. Using non-rehabilitated PCCP for calculations, the cost due to shorter panel lifetime because of loop installation is estimated at $560 per loop detector, which is about 25% of the installation cost (this excludes the user cost associated with traffic delay).
- **Cost attributable to traffic delay (user cost)**. The user cost due to traffic delay caused by lane closures can be a significant part of the overall cost of loop installation (around 60% for a 4 lane freeway and about 40% for a 5 lane

freeway) if loop installation is the only reason for closing lanes. However, loop detectors are typically installed when lanes are closed for other reasons.

- **Cost comparison between loop and video detectors**. When compared for a 4-lane freeway the inclusion of user costs for loop detector installation makes total lifecycle costs between loop and video detectors comparable and, in situations with high traffic and inexpensive video detectors, can sometimes result in video lifecycle costs being less. While this does not suggest video detectors are universally less expensive (in fact, they are usually more expensive), it does indicate that user costs are important to include in comparing detector costs.

6.2 Recommendations

The following recommendations are made:

- **Continue using circle loop detectors**. The shape of loop detectors matters for performance of the pavement, and even though the comparison between various shapes may not be accurate because of different installation times, the results indicate that circle loops have less impact on the panel cracking than rectangular shapes. WSDOT has realized this and now only uses circle loops for new installations.
- **Even considering potential PCC damage, loop detectors are still a cost competitive means of traffic detection**. The cost comparison between loop and video detection shows loop detectors are still a more economical solution for traffic detection than video detectors in most situations. Table 23 shows that the lifecycle cost of a loop detector is estimated at between $3,320 and $5,740 (with

$560 due to increased pavement damage and $1,260 to $3,380 due to user delay). This compares to the lifecycle cost of a video detector estimated at between $5,300 and $26,300 (with no cost for pavement damage or user delay). If circle loops are used the cost due to pavement damage is likely to be even less.

- **Further comparison**. One other comparison method with potential would be to compare the LEPs with the adjacent LFPs on either side of the LEP.
- **Reevaluate user cost**. The simulation for this study used evening traffic volumes (8 p.m. to midnight) but it may be more reasonable to use early morning volumes (say, midnight to 5 a.m.). This could potentially result in lower estimated user costs.
- **Compare loop detection to other detection methods beyond video**. Other traffic detection systems may compare differently to loop detectors.

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