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Health of California's Loop Detector System

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Health of California's Loop Detector System: Final Report for PATH TO 6300

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Abstract

The California Department of Transportation (Caltrans) freeway *sensor network* has two components: the *sensor system* of 25,000 inductive loop sensors grouped into 8,000 vehicle detector stations (VDS) and covering 30,500 freeway direction-miles; and the *communication network* over which the sensor measurements are transported to Caltrans Traffic Management Centers.

The sensor network is virtually the only source of data for use in traffic operations, performance measurement, planning and traveler information. However, the value of these data is greatly reduced by the poor reliability of the sensor network: On a typical day in 2005, only 60 percent of the statewide sensor network provided reliable measurements.

This is the report of an empirical study of the reliability of the sensor network based on two data sets. The first set, obtained from PeMS, consists of a daily summary of the quality of data received from each loop sensor in Caltrans Districts 4, 7 and 11 during the 27 month observation period January 2005–March 2007. The second data set consists of reports of field inspections of more than 4,000 loops each in Districts 4 and 7 during December 2005–December 2006 as part of Caltrans' Detector Fitness Program.

The study proposes and calculates three metrics of system performance: *productivity* is the fraction of days that sensors provide reliable measurements; *stability* is the frequency with which sensors switch from being reliable to becoming unreliable; and *lifetime* and *fixing time*—the number of consecutive days that sensors are continuously working or failed, respectively. Productivity measures the performance of the sensor system; stability measures the reliability of the communication network; lifetime and fixing time provide more detailed views of both components of the sensor network.

These metrics are used to evaluate the differences in system performance in Districts 4, 7 and 11. Productivity in District 11 is much better than in Districts 4 and 7; District 4 is slightly worse than District 7. A significant part of the productivity difference is due to the large number of sensors in Districts 4 and 7 that never worked during the 27 month observation period.

The stability metric shows that the communication network in all three Districts suffer short-term outages; again, District 4 is the worst and District 11 is the best. The outages are likely due to the communication network technology, including protocols, that is used in the different Districts.

The metrics are also used to evaluate the effectiveness of the Detector Fitness Program (DFP). The DFP is unlikely to be cost-effective: two-thirds of the visited loops show no improvement in system performance, the remaining one-third show marginal improvement. Simple suggestions for a more effective design of the DFP are offered.

Lastly, the report proposes a statistical model of sensor failure that could be used in a scientific approach to the maintenance and replacement of the sensor system.

Keywords: Sensor network reliability; loop detectors; Detector Fitness Program; freeway detector system

Executive Summary

The California Department of Transportation (Caltrans) freeway *sensor network* has two components. The first component is the *sensor system* comprising 8,000 vehicle detector stations (VDS) that group 25,000 inductive loop sensors located on the mainline and ramps. The sensor system produces 30-second averages of vehicle occupancy and volume measured by each sensor. The second component is the *communication network* which transports these data to the Traffic Management Centers (TMCs) in each District.

The sensor network is virtually the only source of data used by a District TMC to make freeway operational decisions. The data are also archived in the Performance Measurement System or PeMS, which processes them for use in performance analysis, planning and traveler information.

The value of the data from the sensor network is greatly reduced by its poor reliability. On a typical day in 2005, only 60 percent of the sensor network provides reliable measurements. The poor reliability seriously degrades the quality of traffic operations and planning decisions. In an attempt to improve reliability, Caltrans launched the Detector Fitness Program (DFP) for the 12-month period beginning December 2005.

This is a report of an empirical study of the reliability of the Caltrans sensor network and the effectiveness of the DFP. The study was conducted under PATH Task Order 6300, "Innovative Topic: Maintaining the health of the Caltrans loop detector system."

The study proposes three sensor network performance metrics: productivity, stability and lifetimes. *Productivity* is the fraction of days that sensors provide reliable measurements; it measures reliability of the sensor system. *Stability* is the frequency with which sensors switch from providing reliable measurements to becoming unreliable; it measures reliability of the communication network. *Lifetime* is the number of consecutive days that sensors continue working before they fail, and *fixing time* is the number of successive days that sensors remain in a failed state before being fixed; they provide detailed views of the reliability both of sensor system and communication network.

The conclusions of the study are grouped under District Performance, and DFP Evaluation.

District Performance

District 11's sensor network is much more reliable than District 7, which is more reliable than District 4. The difference is reliability can be analyzed in terms of three sensor groups:

1. A significant fraction of sensors had *always failed* during the study period in District 4 (24%) and District 7 (16%); District 11 had few (3%) always failed sensors. Always failed sensors are likely caused by permanent hardware faults in the sensor system (broken loops, missing parts in the controller, etc.) or, in some cases, misconfiguration.

2. A significant fraction of sensors had *always worked* in District 11 (40%) in contrast with District 4 (0%) and District 7 (4%). The difference is likely due to a communication failure diagnosed by PeMS as 'insufficient number of samples' received. Elimination of this failure state would increase the fraction of always working sensors from 0 to 40% in District 4, from 4 to 30% in District 7, and from 44 to 79% in District 11.

3. A majority of sensors are neither always failed nor always working: they fail and 'spontaneously' recover more than once. Sensors in this group fail more frequently and for longer

periods in Districts 4 and 7 compared with District 11. The failures are likely due to failures in the communication network.

Detector Fitness Program

The DFP resulted in 4,578 visits to 3,244 individual loops in District 4 and 4,732 visits to 3,192 individual loops in District 7. The suspect loops were selected on the basis of the PeMS report of loop status on a *single* day. The DFP records claim that 33% of visited loops in District 4 and 52% in District 7 were fixed. In fact the 'success' rate is much lower.

1. 27% of the visited sensors in District 4 and 16% in District 7 had always failed. The records report that only 9% of these sensors were fixed. In fact, of the sensors that were claimed fixed, only 40% in District 4 and only 24% in District 7 worked for two or more days after the visit. Thus the actual success rate for visits to always failed sensors is must less than 5%.
2. The productivity of loops that were claimed to be fixed improved slightly after the visit; surprisingly, the productivity of loops that were *not* claimed to be fixed improved by almost the same amount. It seems that the improvement comes largely from loops for which crews found hardware faults: 'missing equipment' or 'modem issues'.
3. The stability of loops that were visited was unchanged by the visits. Thus the DFP program in its present form cannot improve the communication network.
4. The maximum productivity improvement in Districts 4 and 7 from the Detector Fitness Program is about 10%. Thus the DFP in its present form cannot significantly improve the performance of the Caltrans sensor network.

Recommendations

Loop detector technology is obsolete. The sensor system consists of many subsystems, failure in any of subsystems puts the associated sensor in a failed state. The sensor system cannot be remotely diagnosed, so the cause of failure can be accurately determined only by an expensive field visit. The communication network technology is also obsolete. In Districts 4 and 7, the communication protocol does not re-transmit lost packets. The tests that PeMS performs on received samples does not check for accuracy of the sensors. If such a check were done, the performance of the sensor network would be significantly worse. The following *tentative* recommendations are suggested by the analysis.

1. The always failed sensors—which account for between 14 and 25% of failed sensors in Districts 4 and 7—cannot be fixed by the DFP. It would be much more cost-effective to replace them. More generally, loop sensors should not be replaced by other loop sensors.
2. The selection of loops to be visited by the DFP should not be based on a single day of data from PeMS, but on the time series of performance as done in this study. A selection procedure can be designed that will increase the chance of success from a DFP visit.
3. Sensors on ramps perform worse than mainline sensors, with performance in District 7 much worse than in District 11. Since District 4 has no ramp sensors registered in PeMS, it is not possible to determine their performance.
4. The analysis cannot pinpoint the reason why the sensor network in District 11 is so much superior to District 4 and 6. It is likely that the disparity is the result of a history of good maintenance in District 11 and a history of neglect in Districts 4 and 7. It is unlikely that this neglect can be compensated by more resources devoted to the DFP. A more cost-effective process is likely to result from selective replacement by a modern sensor network.

In conclusion, if the sensor network is to provide the data of a quality that is adequate to meet the needs of the Strategic Growth Program, the sensor network should receive more serious attention and resources than that provided by the Detector Fitness Program.

1 Introduction

The freeway *sensor network* of the California Department of Transportation (Caltrans) has two components: a sensor system and a communication network. The statewide sensor network is divided into twelve parts, each built, operated and maintained by one Caltrans District.

The statewide *sensor system* consists of 25,000 sensors located on the mainline and ramps, and grouped into 8,000 vehicle detector stations (VDS). Each sensor records the presence of a vehicle above it. The measurements are electronically processed in the VDS to produce 30-second averages of vehicle counts or volume and vehicle occupancy.[1] Over 90 percent of the sensors use inductive loops, most of the remaining use radar detectors. Following successful tests, wireless sensor network technology is being introduced. The current loop-based system has a replacement cost of $320 million and is very expensive to maintain.

The *communication network* transports data packets from each VDS to its District Traffic Management Center (TMC). Based on these data the District Advanced Traffic Management System (ATMS) makes decisions about traffic operations. A copy of the data packets is also sent to the freeway Performance Measurement System (PeMS), which archives the data and processes them in different ways to generate a variety of freeway system performance measures. The communication network is built out of communication links that employ different technologies. For example, wireless GPRS links predominate in District 4; telephone land lines are widely used in Districts 7 and 11. The communication network comprises owned and leased facilities. The owned facilities cost $325 million. Caltrans incurs an annual communication network operating cost of $19 million.

As noted above, each District builds, operates and maintains the sensor network in its area. The sensor system in the largest District (District 7) covering Los Angeles and Ventura counties has 8,700 loop sensors; the nine-county San Francisco Bay Area District 4 has 4,600 loop sensors; and District 11, covering San Diego and Imperial counties, has 3,100 loop sensors. We study the sensor networks in these three Districts, first using data from PeMS.

PeMS expects to receive from each sensor one sample (packet) every 30 seconds. Based on the number and quality of the samples that it actually receives from a sensor on a given day, PeMS designates that sensor as 'good' or 'failed' for that day. The fraction of failed sensors summarizes the reliability of the sensor network for the entire state, an individual District or freeway.

Figure 1 plots the percentage of *failed* sensors for each day from 10/10/2005 to 12/31/2005 for the whole state and for Districts 4, 7 and 11. The sensor network has very poor reliability, with 35 percent of sensors statewide considered failed on any given day. The reliability varies widely by District: District 4 had 40 percent, District 11 had 5 percent, and District 7 had 35 percent failed sensors.

The poor reliability of the sensor network, and the pressing need to use sensor data for better freeway operations decisions, led Caltrans to launch the Detector Fitness Program (DFP) beginning December 2005. The goal of the DFP was to significantly raise the reliability of the statewide sensor network. Over the next 12 months, crews made 9310 visits to sensors in the field in order to diagnose why they had failed and, if possible, to fix the failure. As will be seen later, the resulting improvement in the reliability of the sensor network is measurable. But the improvement is small and it seems clear after 12 months of the DFP that by itself it cannot significantly improve reliability. The DFP produced detailed reports, and our analysis of those reports explains why the impact of

[1] In some cases, a pair of sensors form a 'speed trap' and provide a measurement of speed.

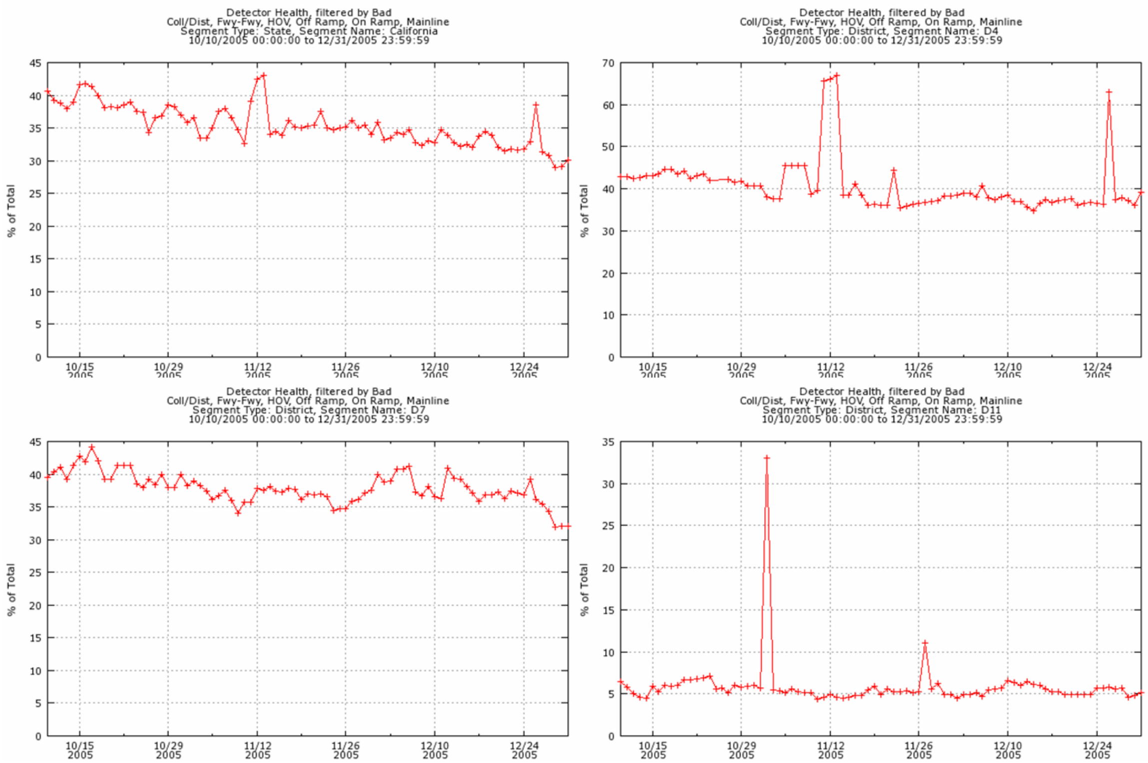


Figure 1: Daily fraction of failed sensors for the statewide system, and Districts 4, 7 and 11 from 10/10/2005 to 12/31/2005.

the DFP is limited.

Most sensors behave like light bulbs: once they fail, they stop functioning for ever. The freeway sensors are quite different: they repeatedly fail and then 'spontaneously' recover from failure, as is evident from the oscillations in Figure 1. Thus, metrics designed to measure the reliability of systems with light bulb-like failures cannot be used for the freeway sensor system. The study proposes three different ways of measuring the reliability of the freeway sensor system: productivity, stability, and lifetime and fixing time.

Productivity is the distribution of the fraction of days that sensors provide reliable measurements. *Stability* is the distribution of the frequency with which sensors switch from providing reliable measurements to becoming unreliable. *Lifetime* is the distribution of the number of successive days that sensors continue working before they fail, and *fixing time* is the distribution of the number of successive days that sensors remain in a failed state before being fixed. The study uses these metrics to compare the reliability of the sensor networks in Districts 4, 7 and 11, as well as to evaluate the effectiveness of the Detector Fitness Program.

The remainder of this report is organized as follows. Section 2 describes the sensor network in a way that shows the kinds of hardware and software faults that can lead PeMS to declare a sensor failure. Section 3 summarizes the two data sets that are used. Section 4 gives the distribution of sensors on different highways.

Section 5 considers sensors that are always in a failed state, and argues that these are likely to be a software configuration error; hence they are excluded from most of the subsequent analysis.

Section 6 introduces the scope chart, which gives a visual summary of the state of the sensor network in an entire District over a period of two years.

Section 7 defines productivity and computes the productivity of the three Districts. Section 8 defines and evaluates stability. Section 9 calculates the lifetime and fixing time distributes.

Section 10 focuses on the overall communication network and attempts to evaluate its failures. Section 11 attempts to evaluate the failures of individual communication links. Section 12 analyzes the Detector Fitness Program and attempts to evaluate its effectiveness. Section 13 collects some conclusions.

Appendix A proposes a Markov chain model of failure and recovery. Appendix B exhibits some fragments of the DFP data sheets. Appendix C explains why the number of sensors in District 4 varies from year to year.

2 Sensor fault description and PeMS failure states

To understand how data are collected and what faults can occur we describe how the sensor network works. Figure 2 is a schematic of the sensor network in District 4. At a particular VDS location, there is a sensor in each lane of the freeway. In more than 90 percent of the locations the sensor is an *inductive loop*, represented by the little circles in the figure. Sensors from the different lanes are connected through a *pull box* to a *controller cabinet* on the side of the road.

The cabinet includes a *170 controller* and a *modem*. The controller *detector cards* process each sensor's measurements to produce 30-second averages of vehicle occupancy and volume, and format these data into a packet, which includes fields indicating the VDS and sensor IDs (identifiers). The cabinet receives power from a local power line.

The TMC receives the data packets from the controller over a digital *communication network*. The network has two parts, one of which is Caltrans-operated and the other is Telco-operated.

A Caltrans-operated *field line* connects the controller cabinet and modem to the Telco demarc box; optionally a *field bridge* connects multiple controllers to the Telco demarc box. A *Telco bridge* connects multiple demarc boxes to a *TMC Line* inside the Telco network. The TMC Line connects to the front-end processor (FEPT) of the District TMC. Up to 20 controllers may share the same Telco line, the different controllers being distinguished by a *Drop ID*.

The FEPT received data by polling the controller modems. The received packets are forwarded to the District ATMS; a copy is also forwarded to PeMS.

Caltrans deploys several variations of the sensor network. A small fraction of the sensors use radar to detect the presence of a vehicle. However, the radar-based systems also produce data packets with the same format. There is a greater difference in the communication network. Some controller cabinets in District 7 are connected to the TMC over Caltrans-owned optical fiber links. More significant is the use of wireless links rather than land lines as in the figure. For example, District 4 uses the GPRS data service.

Thus the overall sensor network combines several hardware and software subsystems. Each subsystem is a potential source of failure. The main subsystems are the inductive loop; the detector card for each sensor; the controller; the Caltrans-operated communication sub-network; and the Telco-operated communication sub-network.

When PeMS receives a data packet, it consults a *configuration table* to interpret the data packet. The table contains meta information that helps determine whether the VDS and sensor IDs in the packet are valid and where the sensors are located (mainline, ramps). If a packet contains an ID that is not recognized by the table, the packet is discarded. Conversely, if there is no packet corresponding to an ID in the table, it is assumed that there is a failure in the system corresponding to that sensor.

Every midnight, PeMS examines the sequence of (data) samples received from each detector; subjects

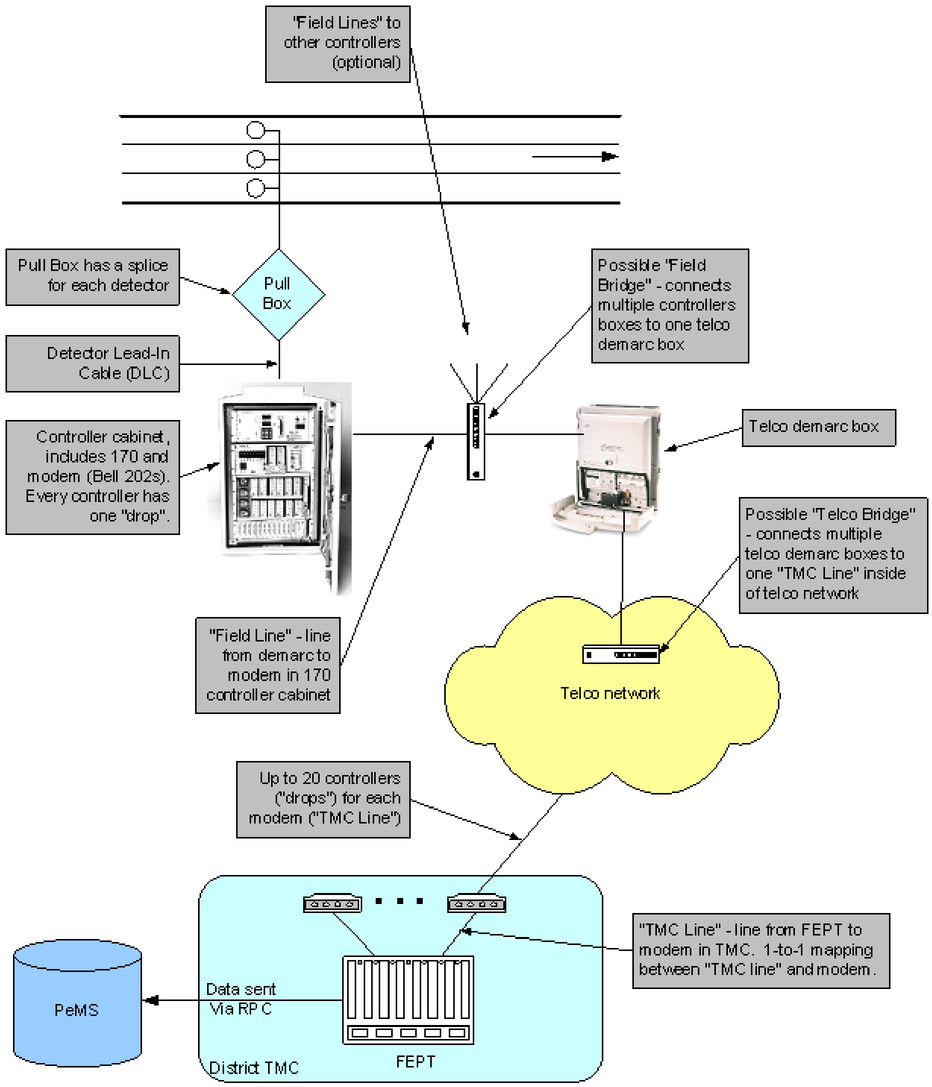


Figure 2: The configuration of the sensor network in District 7

the sequence to a set of statistical tests; and classifies the detector 'health' for that day into one of 10 *diagnostic states* displayed in the first column of Table 1. A correctly functioning detector should daily provide 2,880 30-sec samples with reasonable values. The statistical tests involve the number of received samples and their values. The second column of the table indicates the nature of the tests, and a detailed description is available in [1].

The first nine diagnostic states indicate failure; the tenth state, 'good', indicates a functioning detector. The plots in Figure 1 refer to the daily fraction of failed sensors.

Comparing the configuration of the sensor network in Figure 2 with Table 1 we see that knowledge of the sample sequence received by PeMS from a particular sensor is not enough to uniquely relate a failure diagnostic state with an actual hardware or software fault. For instance, if a sensor delivers insufficiently many samples or no samples at all, this may be due to the controller being down or to a failure of a communication link or an error in the configuration table. Therefore we will aggregate the 10 diagnostic states provided by PeMS into two or three 'macro' states: *good*, *sensor system failure*, and *communication network failure*. Detailed fault analysis will be conducted on data from the Detector Fitness Program since those manually compiled records are obtained from a field visit.

Diagnostic State	Description	Detector Types
Line Down	No detector on the same communication line as the selected detector is reporting data. If information about communication lines is not available this state is omitted.	ML, Ramps
Controller Down	No detector attached to the same controller as the selected detector is reporting data. This may indicate no power at this location or the communication link is broken.	ML, Ramps
No Data	The individual detector is not reporting any data, but others on the same controller are sending samples. This may indicate a software configuration error or bad wiring.	ML, Ramps
Insufficient Data	Insufficient number of samples are received to perform PeMS diagnostic tests, while other detectors reported more samples.	ML, Ramps
Card Off	Too many samples with an occupancy (for ML and HOV detectors) or flow (for ramps) of zero. The detector card (in the case of loop detectors) is probably *off*.	ML, Ramps
High Val	Too many samples with either occupancy above 70% (for ML and HOV detectors) or flow above 20 veh/30-sec (for ramps). The detector is probably stuck *on*.	ML, Ramps
Intermittent	Too many samples with zero flow and non-zero occupancy. This could be caused by the detector hanging on.	ML
Constant	Detector is stuck at some value. (PeMS counts the number successive occurrences of the same non-zero occupancy value.)	ML
Feed Unstable	The data feed itself died and there were insufficiently many samples during the day to run the tests. On days where this occurs we mark the detectors that were previously good as good and the ones that were previously bad as Feed Unstable.	ML, Ramps
Good	Detector passed all tests	ML, Ramps

Table 1: Diagnostic states

3 Data used

We describe the data used in the study and then the pre-processing steps taken to convert the data into a standard format used in the subsequent analysis. Two data sets are used.

The first data set consists of the sequence or time series of daily sensor diagnostic states in PeMS for each loop in Districts 4, 7 and 11 as described in Table 1.[2] The loops considered in the study are those that were listed in the PeMS configuration table on March 31, 2007. For each loop the sequence of days spans 27 months from January 1, 2005 to March 31, 2007; for loops that were installed on a later date, the sequence begins later.

The second data set comprises records from the Detector Fitness Program (DFP) for Districts 4 and 7. These records were created by crews following a field visit to a loop. The records are textual and their format is not standardized; hence they require some interpretation on our part, as explained next.

For District 7, the visits occurred in clusters between December 12, 2005 and August 2, 2006. The records corresponds to a total of 4,732 visits. 3192 individual detectors were visited, implying that several detectors were visited more than once. For different clusters, the data are recorded in different ways on a spreadsheet, possibly because there were different crews. Each row of the spreadsheet

[2] We use 'sensor', 'loop' and 'detector' interchangeably.

corresponds to a visit to an individual loop. Typically, the records contain the following fields:

- Location: comprising the Detector Station (VDS) to which the loop is connected, lane number, highway name, highway direction, and postmile.
- Visit date: typically the date the loop was visited, but sometimes the date the record was entered in the system. It is safe to say that the sensor was visited before this date.
- Problem type: typically a textual description of either the diagnostic state reported by PeMS or the type of problem encountered.
- Related cause: typically the failure cause as surmised by the crew, frequently the name of a broken or missing hardware part.
- Solution: typically the steps taken towards the solution of the problem, and whether the problem was successfully resolved.
- Status: the PeMS diagnostic state after visit.

The column titles are not uniform across different spreadsheets for District 7. For example, sometimes solution and problem type are described in an extra column labeled 'Comments'.

For District 4, the records summarize a total of 4,578 visits between December 12, 2005 and December 30th, 2006. 3244 individual detectors were visited. No visits were reported during February 7, 2006–April 10, 2006 and August 3, 2006–December 3, 2006.

District 4 records are similar to those for District 7, although for some records, a manually entered code is given for the cause of failure together with the solution. This code is not fully utilized in this paper because it mixes the cause of failure with the possibility of solution.

3.1 PeMS data pre-processing

Let the time series $s_i(n)$ denote the diagnostic state as determined by PeMS for sensor i on day n; $s_i(n)$ takes one of the 10 values listed in the first column of Table 1. We merge several diagnostic states together to obtain a new time series s_i^*:

$$s_i^*(n) = \begin{cases} 1 & \text{if } s_i(n) \in \{\text{Good}\} \\ 0 & \text{if } s_i(n) \notin \{\text{No Data,Controller Down, Good}\} \\ -1 & \text{if } s_i(n) \in \{\text{No Data,Controller Down}\} \end{cases} . \tag{1}$$

In some cases (as will be made clear), we modify the conditions above to

$$s_i^*(n) = \begin{cases} 1 & \text{if } s_i(n) \in \{\text{Good}\} \\ 0 & \text{if } s_i(n) \notin \{\text{No Data, Insufficient Data, Controller Down, Good}\} \\ -1 & \text{if } s_i(n) \in \{\text{No Data, Insufficient Data, Controller Down}\} \end{cases} . \tag{2}$$

The aim of this coding scheme is this. $s_i^*(n) = 1$ means that both the sensor system and the communication network associated with loop i were functioning on day n. $s_i^*(n) = 0$ means that the communication network associated with loop i on day n was functional, since some packets were received ($s_i(n) \neq$ No Data), but there was a failure in some part of the sensor system. Lastly, $s_i^*(n) = -1$ corresponds to a communication network failure as no data were received. Sometimes, following (2), 'Insufficient Data' is treated as a communication failure.

Thus $s_i^*(n)$ encodes three conditions:

$$s_i^*(n) = 1 \Rightarrow \text{good},\ s_i^*(n) = 0 \Rightarrow \text{sensor system failure},\ s_i^*(n) = -1 \Rightarrow \text{communication network failure}. \tag{3}$$

The aim of the analysis is to understand the persistence of the 'good' state and the occurrence of the two failure states. Note that by using (1) more failures are attributed to the sensor system, whereas by using (2) more failures are attributed to the communication network.

If there is a 'communication network failure' ($s_i^*(n) = -1$), we cannot say whether the sensor system has also failed, because a communication failure masks or *censors* the corresponding sensor system observation. How can we estimate the sensor system state when there is a communication failure?

One approach is to build censored estimators, which can be computationally very expensive and requires a parametric model for sensor system failures. A simple alternative, in keeping with the non-parametric approach we have adopted here, is to fill in the sensor system failure value with its last known value. Thus if $s_i^*(n) = -1$, we set $s_i^*(n) = s_i^*(n-1)$. If $s_i^*(n) = -1$ on the first day of the series for loop i we ignore the series until the very first day for which $s_i^*(n) \neq -1$.

We call the new resulting sequence a *filled* sequence. Filling can be done with respect to a {No Data, Controller Down} state (see (1)) or with respect to a {No Data, Controller Down, Insufficient Data} state (see (2)). Both reflect communication failures. The difference lies in the interpretation of insufficiently many samples received. Could it be that the controller card is damaged, in which case it is a sensor system failure? Or are samples lost, indicating a communication network failure? Wherever necessary we make the distinction during the analysis. A *filled* sequence is one in which {No Data, Controller Down} are filled. A *ND-filled* sequence is one in which states {No Data, Controller Down, Insufficient Data} have been filled.

3.2 Detector Fitness Program data pre-processing

The DFP maintenance records do not follow a uniform format. The recording frequently was not very careful. For example in District 4, 25% of the records report no underlying cause of failure. In District 7, only 4% of the records suffer from this deficiency. Such recording procedures poses an additional challenge to the data analysis.

For each visit to a sensor an entry in the maintenance record is created and the observed failure and actions taken are recorded. One problem is that no systematic way of recording the observed failures was followed. For example the following are typical entries for observed failures:

1. open loops SB lane 3. disabled channels
2. open loop
3. open loops/DLC. should be eb lanes
4. no EBML. DLC not present in cabinet
5. no WBML lane 7
6. new cabinet. no equipment

The first item claims that the sensor was damaged (open loop), and the resulting action was to disable the communication channels. In the third and fourth items, DLC, EMBL and WBML are parts of the sensing equipment, so they characterize "Bad or Missing Equipment" cases. Appendix B displays a fragment of typical spreadsheets that contained the data and some more explanations.

Another problem as seen in the examples above is that the cause for the observed failure and the actions taken are sometimes encoded in the same sentence. More examples can be seen in appendix B. Given the thousands of DFP records, it is not practicable to read the records one by one and encode the information manually for subsequent analysis.

Therefore we used a simple parsing scheme to encode the textual records. We created 9 non-mutually exclusive classes: Upgrade Firmware, Under Construction, Open Loop, Connection Issues, Modem/Card Issues, Reset Equipment, No Power, Other Issues and No reported cause. For each class we seek specific keywords or combination of keywords in the text. If the keywords are observed a '1' is entered for that class for that record; otherwise a '0' is entered. We manually checked many of the assignments made in this way and they worked reasonably well, because failure descriptions use a much smaller vocabulary than freeform text.

Each record also contains an entry that tells us if the sensor was fixed (and thus left working) or not fixed. This entry will be important in analyzing the effectiveness of the DFP. Lastly the analysis uses the recorded visit date as a proxy for the true visit date.

Thus for each visit we end up with 13 variables: the sensor visited, the visit date, whether the sensor was fixed or not, and an indicator of 9 possible non-exclusive failure causes.

4 Sensor distributions

Table 2 gives the total number of sensors in District 4[3], and the highways with the largest number of sensors. The corresponding numbers for Districts 7 and 11 are in Tables 3 and 4. Table 5 shows the sensor distributions per lane for each District. These sensors cover 2,870 miles in District 4, 2,318 miles in District 7, and 2,060 miles in District 11.

Highway	Sensors	(%)
101	1315	22.7%
680	922	15.9%
80	846	14.6%
880	815	14.1%
Other	1884	32.6%
Total	5782	100.0%

Table 2: Sensor distribution for District 4 on March 31, 2007.

Highway	Sensors	(%)
10	1374	15.8%
405	1153	13.2%
5	1068	12.3%
101	733	8.4%
210	604	6.9%
605	592	6.8%
60	556	6.4%
Other	2627	30.2%
Total	8707	100.0%

Table 3: Sensor distribution for District 7 on March 31, 2007.

We consider on-ramp and off-ramp as well as mainline sensors.

[3]See Appendix C for disabled sensors in District 4, which explains differences with respect to PeMS.

Highway	Sensors	(%)
5	716	21.9%
15	656	20.1%
805	426	13.1%
8	479	14.7%
Other	987	30.2%
Total	3264	100.0%

Table 4: Sensor distribution for District 11 on March 31, 2007.

District	Lane 1	Lane 2	Lane 3	Lane 4	Lane 5	Lane 6	Lane 7
4	1531	1515	1379	1043	255	51	7
7	3831	1788	1478	1193	349	52	8
11	1108	956	567	401	177	48	5

Table 5: Sensor distributions in lanes 1-7 on March 31, 2007.

5 always-failed and always-working sensors

Examination of the PeMS diagnostic sequences reveals a significant fraction of sensors that are always failed (i.e., never worked) or always working. We begin by analyzing the statistics of such sensors. Sensor i is called **always-0** if the sensor is assigned a failed state for the entire period T, i.e., $s_i^*(n) = 0, n \in T$. It is called **always-1** if a failed state is never observed for the entire period T, i.e., $s_i^*(n) = 1, n \in T$. T is taken to be one quarter or one year. (See (1) for definition of s_i^*.)

We use filled sequences to count **always-0** and **always-1** sensors, unless explicitly indicated otherwise. This means that communication failures are *not* considered to be faults for this analysis. The type of filled sequence does not affect the **always-0** status, but it does affect **always-1** status, because if 'Insufficient Samples or Data' is regarded as a communication failure, some sequences that include 0 values can become **always-1** .

Table 6 shows the number and percent of **always-0** and **always-1** sensors in the three different Districts. There is a large number of **always-0** sensors in District 4 and District 7 compared to District 11. This discrepancy by itself accounts for a considerable portion of the performance difference between Districts.

Furthermore, District 4 and District 7, in contrast with District 11, have almost no **always-1** sensors. The increase of **always-1** sensors from 2005 to 2006 in District 7 is due in part to sensor misconfigurations that were corrected and in part to the DFP. Notice also that the increase in **always-0** sensors in District 11 is mainly due to the inclusion of ramp sensors in PeMS starting in 2006.

District (Year)	Total	**always-1**	**always-0**
District 4 (2005)	5140	9 (0%)	1171 (23%)
District 4 (2006)	5271	0 (0%)	1327 (25%)
District 7 (2005)	6478	21 (0%)	1090 (17%)
District 7 (2006)	8613	319 (4%)	1399 (16%)
District 11 (2005)	1750	604 (35%)	38 (2%)
District 11 (2006)	3223	1402 (44%)	116 (4%)

Table 6: Failure summary for always failed and always working sensors.

For 2006, we separate mainline from other sensors (located on ramps) and show the distribution of **always-0** sensors. Table 7 shows that ramps have a larger fraction of always-failed sensors. Also, District 4 has no ramp sensors registered in PeMS.

District (Year)	Total Mainline	**always-0**	(%)	Total Other	**always-0**	(%)
District 4 (2006)	5269	1327	25%	2	0	0%
District 7 (2006)	5932	847	14%	2681	552	21%
District 11 (2006)	2162	49	2%	1061	67	6%

Table 7: Failure summary for always failed sensors classified by type (Mainline or Other).

In Tables 6 and 7, we considered communication failures as an actual fault. If we use an ND-filled sequence, which classifies 'Insufficient Data' as a communication failure, then the number of **always-1** sensors increases while the number of **always-0** sensors remains the same, as expected (Table 8). The increase in the number of **always-1** sensors assumes that the sensor system reliability is unchanged during a communication failure. This indicates that at least part of the performance difference among Districts can be attributed to communication network failures.

Comparison of Tables 6 and 8 leads to the following conclusion.

District (Year)	Total	**always-1**	**always-0**
District 4 (2006)	5271	2106 (40%)	1327 (25%)
District 7 (2006)	8613	2590 (30%)	1399 (16%)
District 11 (2006)	3223	2544 (79%)	116 (4%)

Table 8: Failure summary for always failed sensors in ND-filled sequences.

Conclusion 1 The large number of **always-0** sensors in Districts 4 and 7 account for a significant of the poor reliability of their sensor system. If the diagnostic state 'Insufficient Data' is caused by a communication network failure and if this failure can be eliminated, the percent of **always-1** sensors will increase from 0 to 40% for District 4, from 4 to 30% for District 7, and from 44 to 79% for District 11, resulting in a dramatic improvement in the performance of the sensor system as a whole.

To conclude the section, we check how always failed sensors are distributed among different highways and lanes. We only report on District 4, as the results are similar for the other Districts. Figure 3 shows that the distribution of failures is even across highways. Highways with a very large percentage of **always-0** sensors have very few sensors as shown in Figure 3.

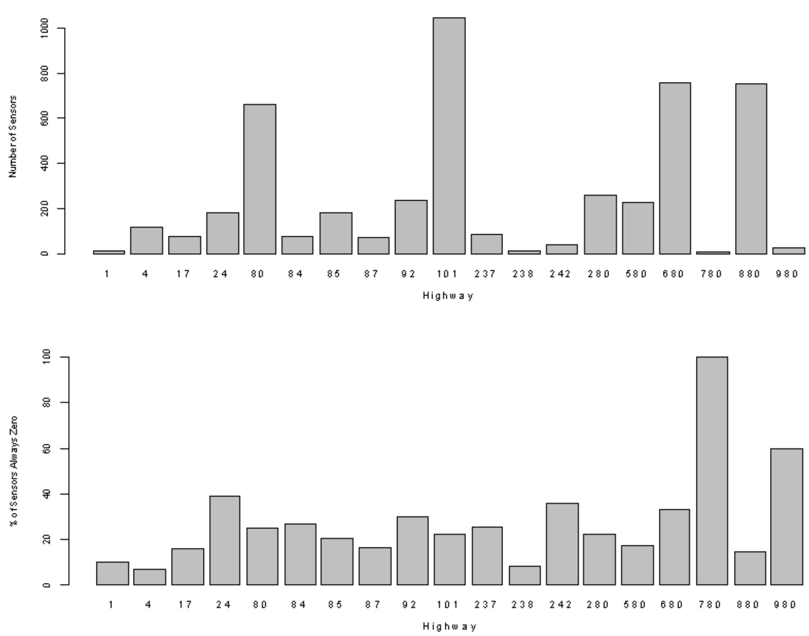


Figure 3: Distribution of number (top) and percent (bottom) of **always-0** sensors by highway for District 4 (2004)

We can similarly analyze the always failed sensor distribution by lane. We choose a particular highway (US-101) for this plot. This highway has a high volume of trucks, which tend to use the slower lanes (lanes with higher number). Figure 4 shows that the outermost lanes have a higher number of failures, suggesting that heavy traffic use may cause more permanently failed sensors. A statewide view is shown in Figure 5.

We can also investigate whether permanent failures of individual loops are caused by failure of the controller itself, in which case all loops attached to the controller would fail. (See 'Controller Down'

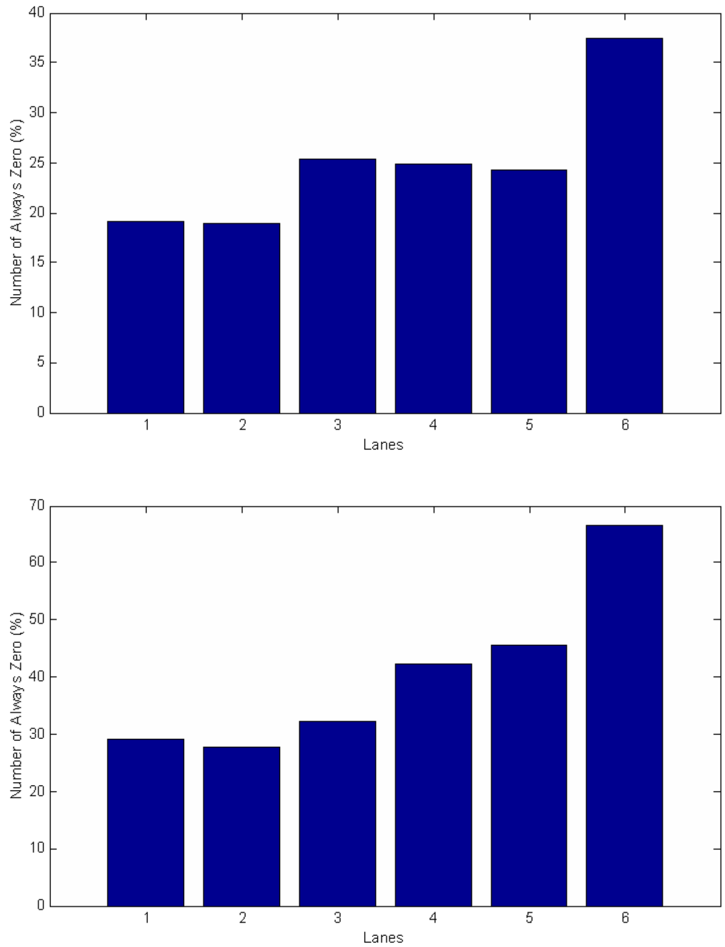


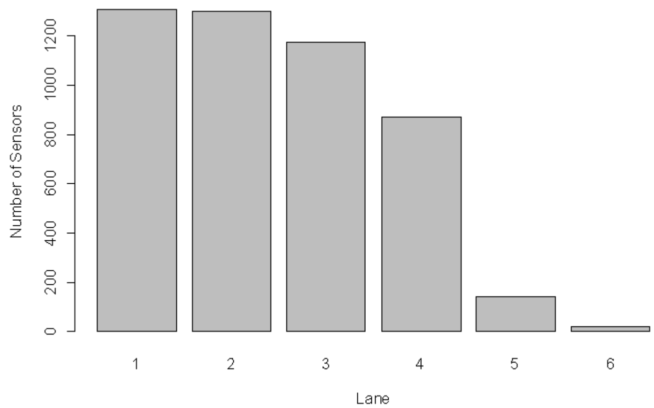
Figure 4: Distribution of number **always-0** by lane for highway US-101 (top) and I-680 (bottom) in District 4 (2004)

in Table 1.) In our case we can conclude that a controller has failed if all the sensors attached to the controller are in **always-0** state for the chosen time period. Figure 6 shows this distribution. About 100 controllers are always failed, whereas about 600 controllers have a few (but *not* all) always failed loops. We may conclude that an always failed sensor is not strongly related to the a possible failure of the controller.

Conclusion 2 Always failed loops are not primarily caused by 'Controller Down' failures.

6 System view

In this section we introduce a novel view—the *scope chart*—of the sensor system state, based on visualizing the fault sequence over time and across highways. This visualization technique provides



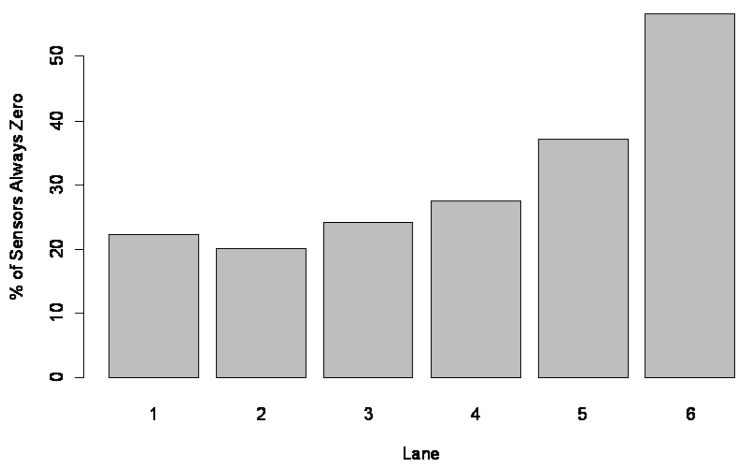


Figure 5: Distribution of **always-0** loops by lane for District 4 (2004)

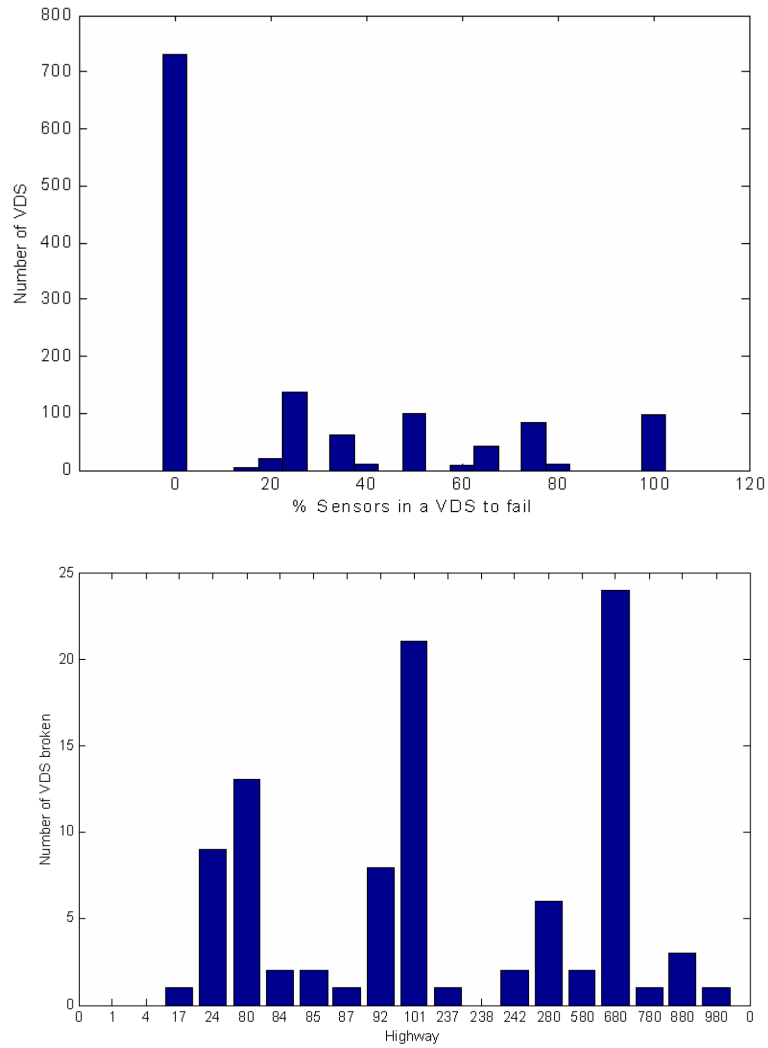


Figure 6: Distribution of fraction of **always-0** loops in a controller (top) and distribution of possible broken controllers by highway in District 4 (bottom) (2004)

a global view of the system or of parts of the system.[4] We first describe how such plot is constructed.

For each sensor i, compute the state sequence $s_i^*(n)$, which assumes values 1 (sensor is good on day n), -1 (communication network failure on day n) and 0 (sensor system failure on day n) (see (1)). The plot is a two-dimensional 'heat' map (1 = red, -1 = blue, 0 = green). The horizontal axis is time in days. (The sequences cover 27 months or 810 days.) The vertical axis corresponds to some ordering of all sensors. In Figure 7 for District 7 all sensors on the same highway are grouped together (beginning with highway I-5 and progressing to I-710) and within each highway group they are ordered by postmile and lanes.

In the chart we can clearly see horizontal red lines representing sensors that worked for long periods. A blue streak in the horizontal direction indicates a sensor that did not report data for a long period. Blue streaks in the vertical direction correspond to days when many sensors sent no samples. This could be caused by a communication network failure in which several TMC lines failed or the FEPT

[4]Scope charts are now a feature of PeMS7.3.

was unable to poll many modems (see Figure 2). Such streaks explain the oscillations observed in the total number of failed sensors in Figure 1. The scope chart also allows us to compare the reliability of different highways.

The scope charts in Figure 7 can be compared with each other. The charts suggest that in general District 11 has a much more reliable sensor system. In particular, there are fewer communication failure streaks in District 11 than in the other two Districts (the blue streaks at the leftmost side of the chart usually corresponds to dates before the sensor was installed into the system). This reinforces the importance of the communication network between the controller modems and the FEPT.

Another ordering is by the number of observed working days, with an increased weight for more recent days. An exponential weight function is chosen, with the parameter tuned so that working days further back in time are considered less valuable then those more current. This gives a boundary curve for the working sensors, such as that shown in Figure 8 for District 7. If the boundary curve is concave, then the system performance is clearly improving over time, whereas a convex boundary curve indicating the system performance is becoming worse.

Two boundary curves can be compared using their shapes as intuitively seen in the figure. By comparing the shape resulting from the dark region, we see that the figure on the right has a larger dark region, implying that more sensors were working in 2006.

Conclusion 3 The scope chart provides an excellent summary of the performance of the sensor network in a District or on a particular highway. It permits comparison of performance across Districts and over time. It is now a feature of PeMS7.3.

7 System productivity

In this section we propose a measure of productivity of a District's sensor network. The measure is computed as follows. Consider a time interval T and a sensor set $\mathcal{M}$ of size M. For each sensor $m \in \mathcal{M}$ we calculate the percent of days d_m that the sensor is working as $w_m = 100[d_m/T]$. The *productivity* of $\mathcal{M}$, $P_{\mathcal{M}}(x),\ x \in [0, 100]$ is the cumulative frequency distribution of w_m:

$$P_{\mathcal{M}}(x) = \frac{1}{M}\sum_{m=1}^{M} \mathbb{1}\left(w_m \le x\right). \tag{4}$$

$P_{\mathcal{M}}(x)$ is the fraction of the sensors that worked for at most x% of days. Evidently, sensor set $\mathcal{M}_a$ has *strictly better productivity* than $\mathcal{M}_b$ if $P_{\mathcal{M}_a}(x) < P_{\mathcal{M}_b}(x)$ for all x. A single number to compare two sensor sets is the *total productivity* (TP) defined as the area above the productivity function,

$$\mathrm{TP}_{\mathcal{M}} = 1 - \int_0^{100} P_{\mathcal{M}}(x)dx, \tag{5}$$

which of course is the empirical average of w_m,

$$\mathrm{TP}_{\mathcal{M}} = \frac{1}{M}\sum_{m=1}^{M} w_m. \tag{6}$$

If we model the sensor state as a two-state ('good' and 'failed') stationary Markov chain, TP is the steady-state probability of the chain being in the 'good' state.

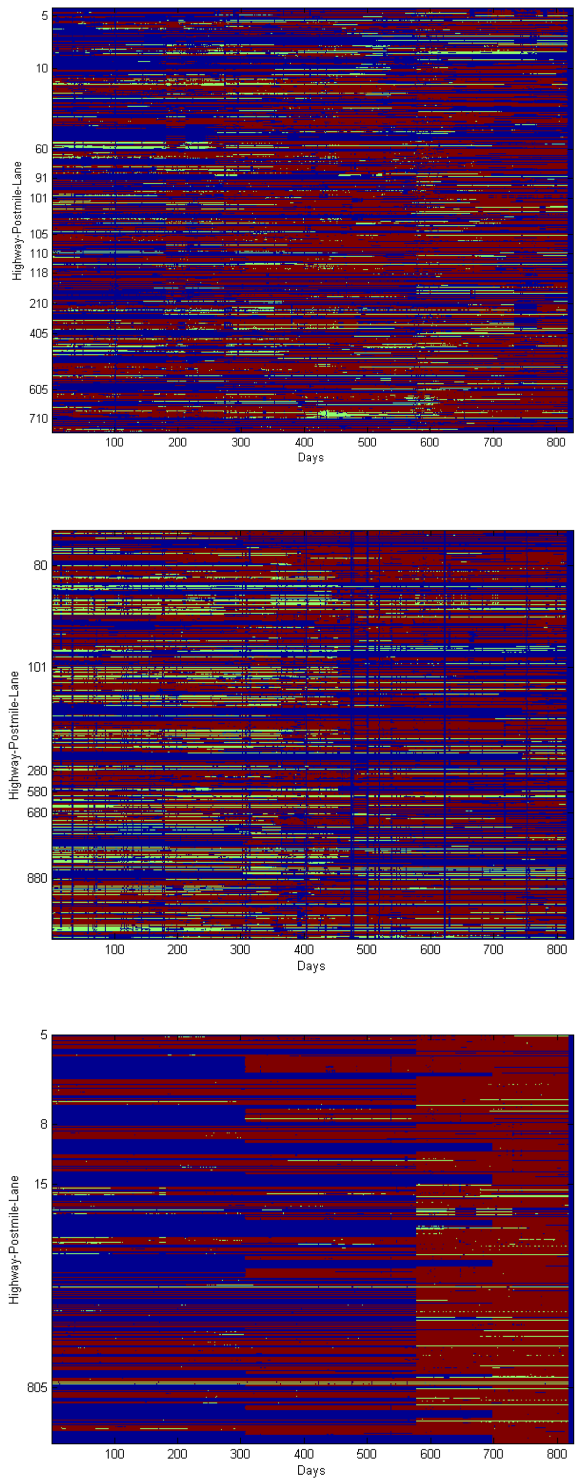


Figure 7: Scope chart ordered by highway, postmile and lane for Districts 4 (top), District 7 (middle) and District 11 (bottom), 2005-2007. Red streaks corresponding to Good state, green to Bad and blue to Communication network failure.

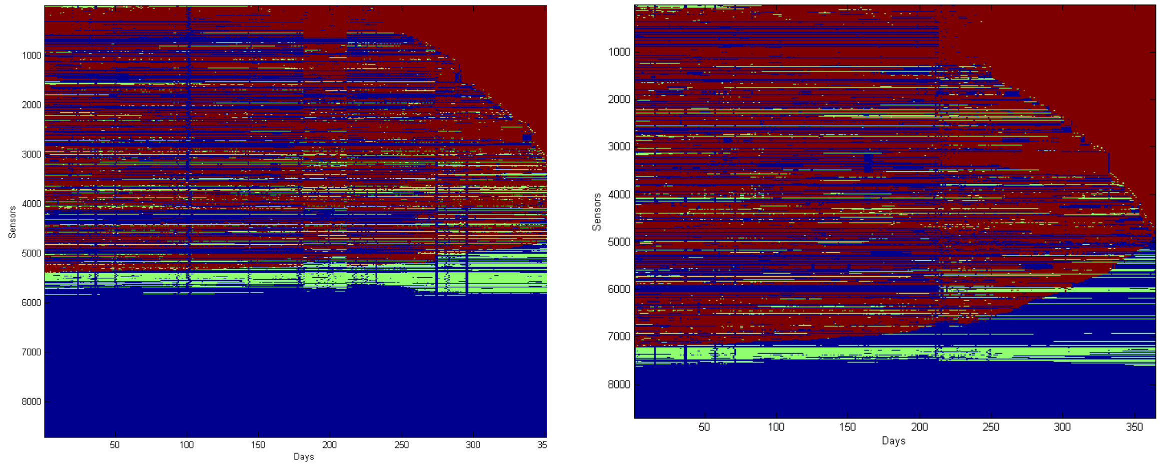


Figure 8: Scope chart ordered by number of ones (more recent), District 7, 2005 (left) and 2006 (right)

7.1 Empirical estimates of productivity

We compute the productivity of the sensor networks in Districts 4, 7 and 11, using the raw (non-filled) data sequence (1). We omit all sensors that are **always-0** for the chosen time horizon. The reason for this choice is that the **always-0** analysis has already been carried out, and these sensors affect the obtained curves and make the interpretation more difficult.

Figure 9 displays the results. For any point on the curve take the y-ordinate (say 20%), determine the corresponding x-ordinate (say 40 days), and interpret the point to mean 20% of the sensors worked for less than 40% of the time. Alternatively, 80 % (100%-20%) of the sensors worked for more than 40% of the time. The total productivity of the sensor network is the area above the productivity curve.

For District 7, productivity in 2006 is strictly better than in 2005, presumably a result of the Detector Fitness Program (DFP). For District 11 productivity remained unchanged, and is strictly better than the productivity of both Districts 4 and 7. For District 4, the median productivity for both years was unchanged ($y = 50\%$), with an improvement for sensors with performance below median in 2005 and worse for those above the median. The effect of the DFP for District 4 is mixed.

To improve our understanding of the productivity of Districts 4 and 7, we calculate the productivity in 2006 of the sensor network in specific highways with the largest number of sensors. Figure 10 shows the results. In District 4, the choice of highway has little influence. In District 7, the sensor network productivity for US-101 and I-405 is significantly better than for I-10 and I-5. Comparing the productivity for these highways during 2005 (Figure 11) we see that I-5 is the worst in both years.

We probe further by examining productivity by lane for selected highways, Figure 12. For US-101 in District 4 and I-10 in District 7 the productivity across lanes is almost identical. But for I-5 in District 7, lane 2-4 are similar, but lane 1 is worse.

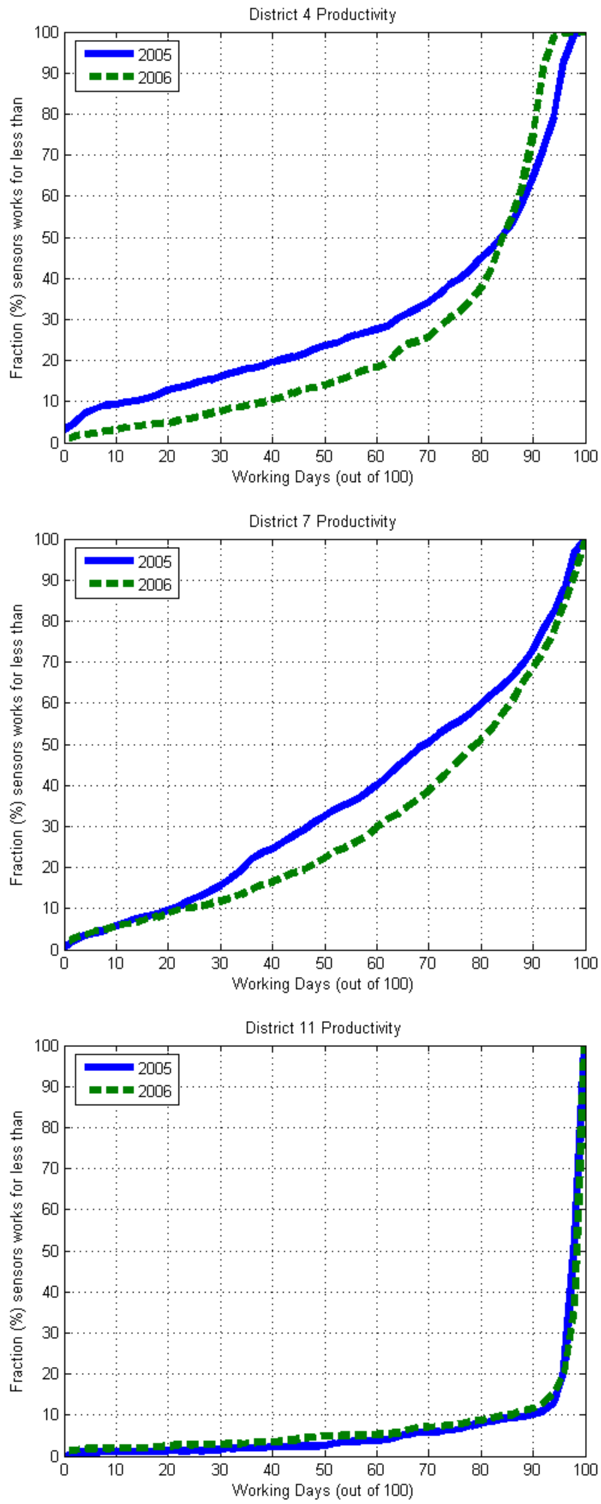
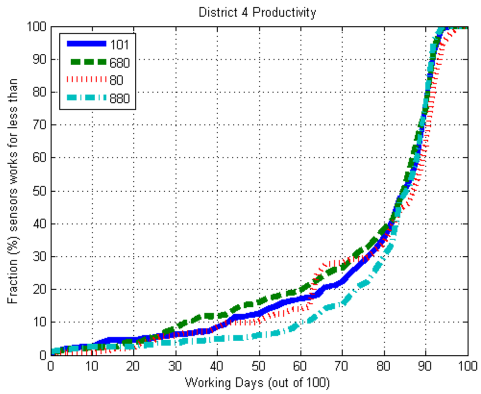


Figure 9: Productivity of District 4 (top), District 7 (middle) and District 11 (bottom), 2005 and 2006



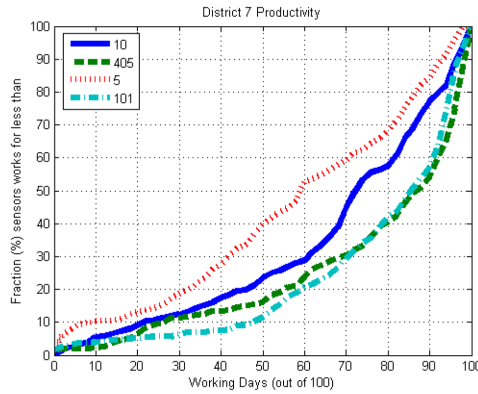


Figure 10: Productivity of District 4 (left) and District 7 (right) for some highways (2006)

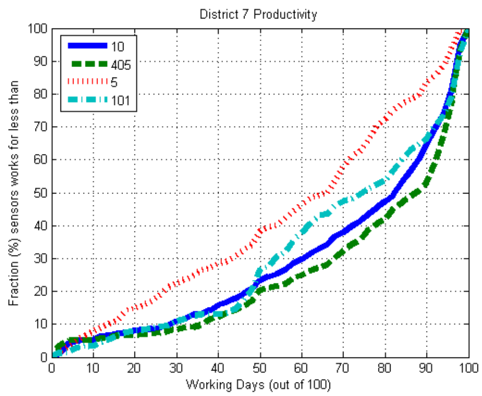


Figure 11: Productivity of District 7 for some highways (2005)

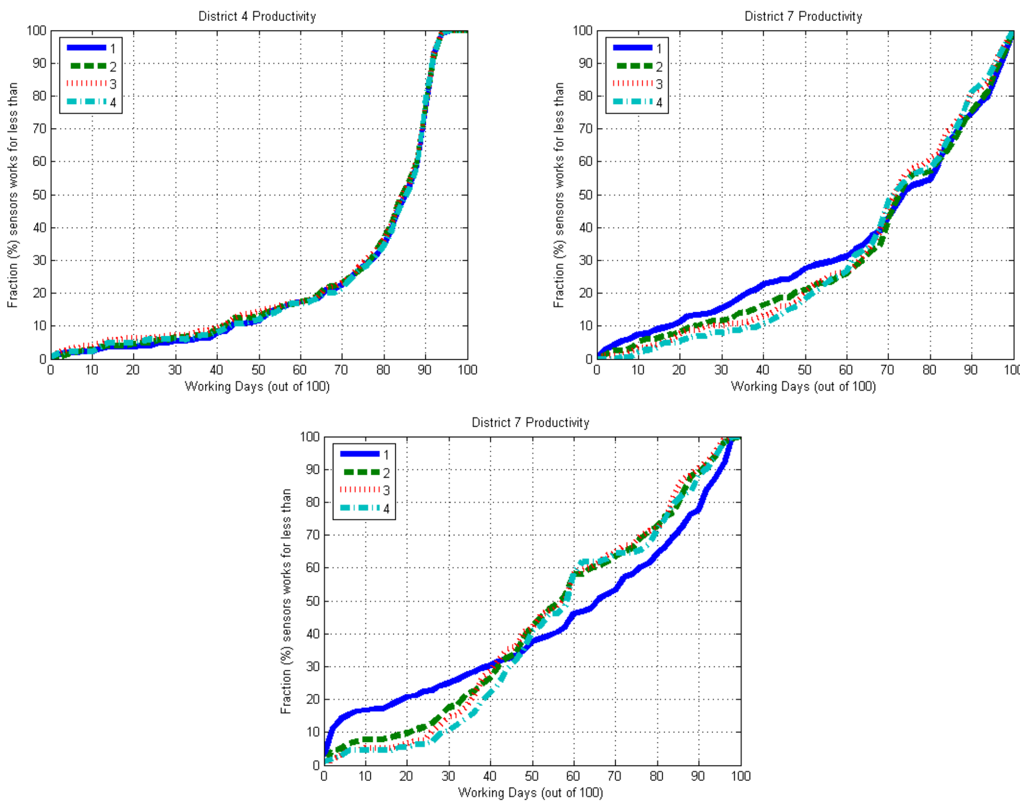


Figure 12: Productivity of US-101 in District 4 (top left), I-5 (top right) and I-10 (bottom) in District 7 (2006)

Conclusion 4 The productivity metric is the most important measure of performance of the sensor network in a District. For District 7, productivity improved from 2005 to 2006, possibly as a result of the Detector Fitness Program. For District 4, there was an improvement in sensors that were performing poorly in 2005. For District 11, productivity was unchanged and remained at its high level. I-5 in District 7 continues to perform poorly. There is no significant variation in productivity by lane.

8 System stability

From Table 6 we know that the majority of sensors switch between good and failed states one or more times. (These are the sensors that are not **always-0** or **always-1** .) Sensors with the same productivity may switch different number of times. We propose a simple system metric that captures this difference.

For a sensor set $\mathcal{M}$ of size M and time interval T, we compute the normalized number of state changes $s_m = (r_{10,m} + r_{01,m})/T$, where $r_{10,m}$ is the number of times sensor m switches from the good state to a failed state during T and $r_{01,m}$ is the number of switches from a failed to the good state. The *stability* of $\mathcal{M}$, $S_{\mathcal{M}}(x),\ x \in [0, 100]$ is the cumulative distribution of s_m:

$$S_{\mathcal{M}}(x) = \frac{1}{M} \sum_{m=1}^{M} \mathbb{1}\left(s_m \leq \frac{x}{100}\right). \tag{7}$$

$S_{\mathcal{M}}(x)$ is the fraction of sensors that switched states on at most x% of the days. The *total stability* TS is the area below $S_{\mathcal{M}}(x)$:

$$\mathrm{TS}_{\mathcal{M}} = \int_0^{100} S_{\mathcal{M}}(x)dx. \tag{8}$$

Sensor set $\mathcal{M}_a$ is *strictly more stable* than a set $\mathcal{M}_b$ if $S_{\mathcal{M}_a}(x) > S_{\mathcal{M}_b}(x)$ for all x. $\mathcal{M}_a$ is on average more stable than $\mathcal{M}_b$ if $\mathrm{TS}_{\mathcal{M}_a} > \mathrm{TS}_{\mathcal{M}_b}$. If we model the sensor state as a stationary two-state Markov chain, its two transitional probabilities are determined by its total productivity and total stability (see Appendix A).

8.1 Empirical estimates of stability

Using the raw data, we estimate the stability of different Districts. We discard sensors that are **always-0** , as they were considered separately. The average stability of the system is just the area below the stability distribution curve.

Figure 13 compares the stability of districts District 4, District 7 and District 11 for 2005 and 2006. For a point on the plot, suppose its y-ordinate is 50% and the corresponding x-ordinate is 5. This means that 50% of the sensors switched 5 or fewer times during a 100 day period. In the figure, District 4 is less stable in 2006 than in 2005, as the stability curve in 2005 strictly dominates 2006. The median number of switches increased from 5 in 2005 to 7 in 2006. This may be due to the large number of changes in the system configuration in 2006 (see Appendix C).

The sensor network in District 7 was more stable in 2006 (median 3) than in 2005 (median 4). Also this District's sensor network is more stable than District 4. In District 11 we see no change in stability between 2005 and 2006. The median number of switches is 1, much better than Districts 7 and 11. Notice also the large number of sensors with 0 number of switches. These are the **always-1** sensors.

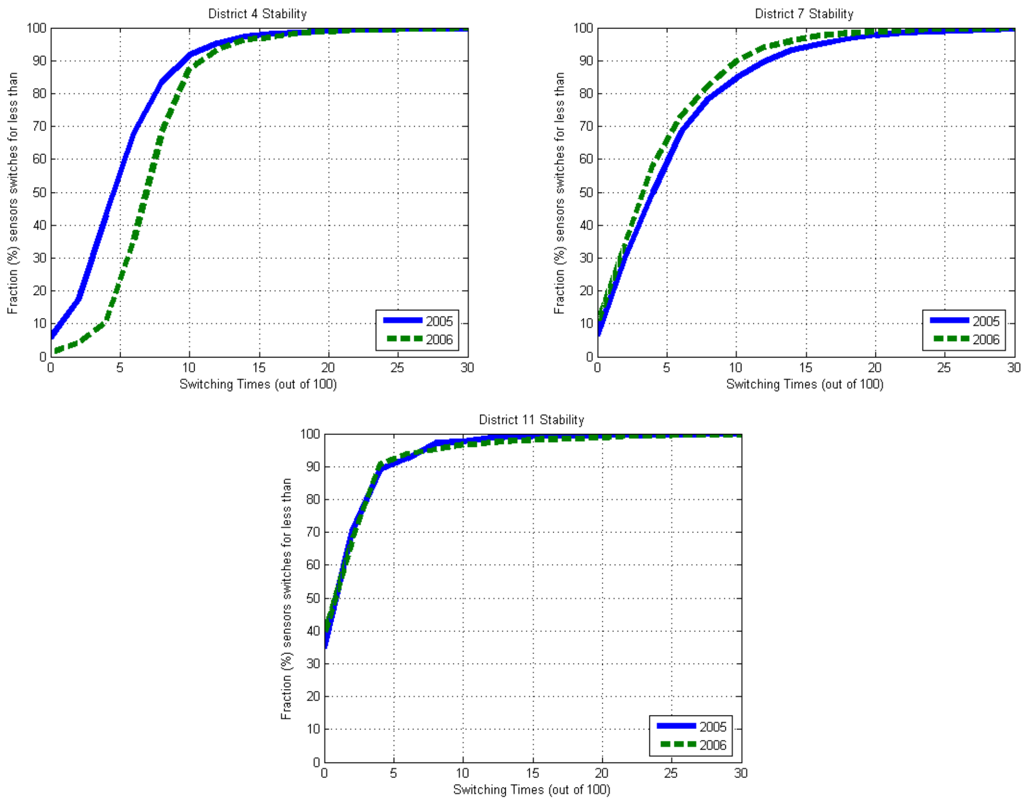


Figure 13: Stability of Districts 4, 7 and 11 (2005-2006)

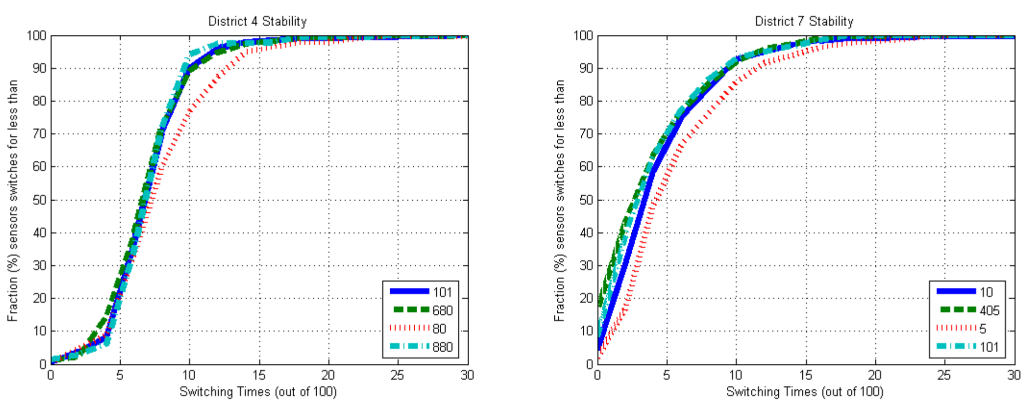


Figure 14: Stability of District 4 and District 7 for some highways (2006)

We drill down further by computing the stability for specific highways in 2006 for District 4 and District 11. Figure 14 displays the results. For District 4, only I-80 is different, being more unstable than US-101, I-680 and I-880. Since the productivity is essentially the same for these highways, this implies that the sensors in I-80 although they worked on average as much as the other sensors, switch more frequently.

In District 7 we see a similar phenomenon for I-5 compared to other highways. In this case I-5 is strictly dominated by its counterparts. This also matches up with the poor productivity of I-5 when compared to other highways. The difference is not extreme (for example the median switching for

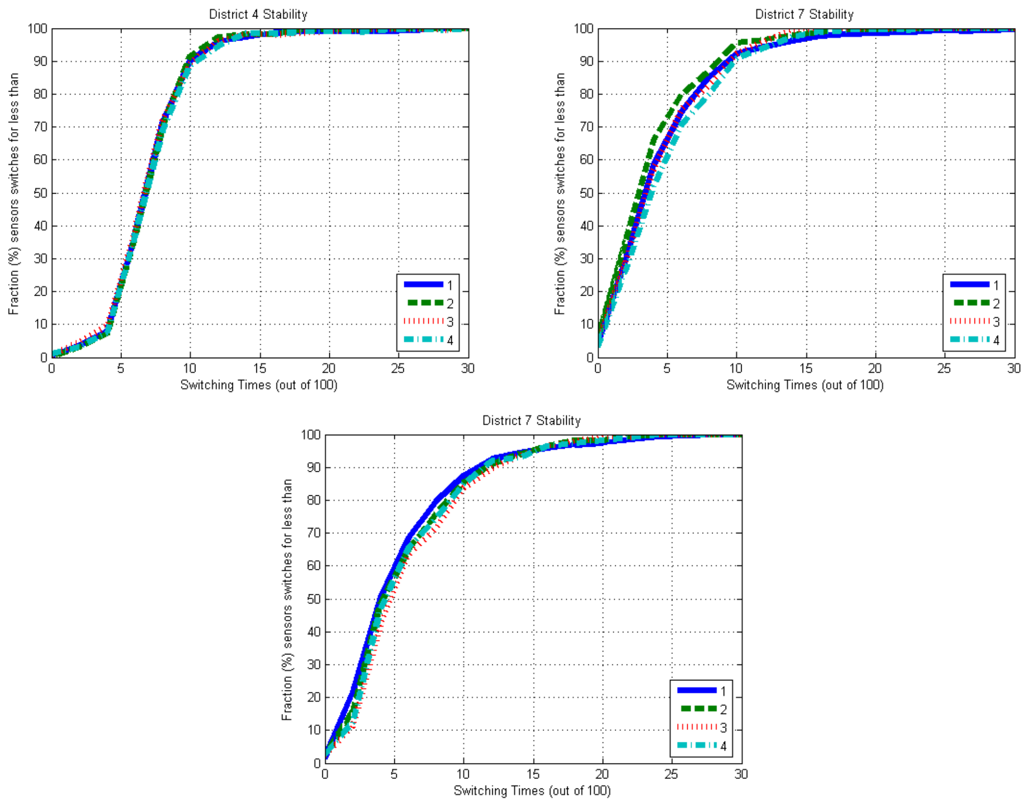


Figure 15: Stability of District 4 for US-101, District 7 for I-5 and I-10(2006)

I-5 is 5, and for the other highways is about 4). This reinforces the hypothesis that there could be some essential difference between the sensor network in I-5 and in other highways.

To conclude this section, we compute the stability in 2006 for selected highways, group the sensors by lane. Figure 15 displays the results. Observe that the stability does not vary by lane in US-101 in District 4 or I-5 and I-10 in District 7.

Conclusion 5 Stability is a measure of how frequently individual sensors switch between working and failed states. The sensor network in District 4 was less stable and in District 7 it was more stable in 2006 compared with 2005; District 11's stability was unchanged and continued to be much better than Districts 4 and 7.

9 Lifetime Estimates

Estimation of *lifetime* or *survival* curves is the standard approach in statistics for characterizing system failures ([3, 4]). In this approach a number of individuals are observed starting at varying initial times and their failure times are recorded. Records of individuals that did not experience failures during the observation period will be right-censored as we don't know when they would have failed. The survival curve is the complement of the cumulative distribution of time to failure. The standard non-parametric estimators of the survival curve are the Nelson-Aalen and Kaplan-Meyer estimators [3, 4]. These estimators are appropriate only for individuals experiencing a permanent failure rather than recurring failures.

In the California sensor network, many failed sensors 'spontaneously' start working again, which is different from the standard survival analysis setting. In the sensor network literature as well recurring failures are usually ignored, but it is an important phenomenon that should be understood [8, 9]. Spontaneous failure and recovery processes could indicate that the loss of performance is not a result of failures in the underlying hardware (which are likely to be permanent), but is rooted in the design choices for the communication network and sensor unit.

We use simple estimates of survival curves, which account for spontaneous recovery. More complicated estimators can be calculated and, in future work, we will investigate and develop parametric lifetime models for the system. We now describe our estimates.

Choose a time period T. The data comprise filled or a ND-filled sequences. For each sensor i, compute the runs of 0's and 1's. A *0-run* is the count of the number of successive days $s_i(n) = 0$; a *1-run* is the count of the number of successive days $s_i(n) = 1$. Each sensor's 0-runs and 1-runs alternate. Denote the set of 0-runs and 1-runs for sensor i by $\mathcal{R}_i^0$ and $\mathcal{R}_i^1$ respectively. We normalize all run lengths by the total number of days the sensor is in the system during T.

Observe that the length of a 1-run is the number of days a sensor remains in a working state before it fails, which we can regard as its lifetime. The length of a 0-run is the number of days a sensor remains in a failed state before it begins to work, which we can regard as the time it takes to get 'fixed' or fixing time. This observation leads to the following estimators.

The first estimate is the *lifetime distribution*, which is the empirical cumulative distribution function for $\mathcal{R}^1 = \bigcup_{i \in \mathcal{A}} \mathcal{R}_i^1$, while the *mean lifetime* of sensor i is

$$\mu_1(i) = \frac{\sum_{r_i \in \mathcal{R}_i^1} r_i}{|\mathcal{R}_i^1|}. \tag{9}$$

The second estimate is the *fixing time distribution*, which is the empirical cumulative distribution function for $\mathcal{R}^0 = \bigcup_{i \in \mathcal{A}} \mathcal{R}_i^0$, while the *mean fixing time* of sensor i is

$$\mu_0(i) = \frac{\sum_{r_i \in \mathcal{R}_i^0} r_i}{|\mathcal{R}_i^0|}. \tag{10}$$

$\mu_1(i)$ is the average time sensor i is working before it fails and $\mu_0(i)$ is the average time it takes to become fixed after it has failed.

We can compute the empirical distributions of the mean lifetime $\mu_1(i)$ and the mean fixing time $\mu_0(i)$. In these distributions, each sensor contributes a single number. The difference between the 1-run distribution and the mean lifetime distribution, is that the former represents a system property (for example, sensors that are **always-1** contribute less to the distribution, as they have a smaller number of runs), whereas the latter is a distribution of the lifetime property of individual sensors.

9.1 Runs distributions

Figure 16 shows the 1-run distribution for Districts 4, 7 and 11. As usual, we do not consider **always-0** sensors. For District 4, 80% of the 1-runs last 50 or fewer days during a one-year period, with little difference between 2005 and 2006. For District 7 we see an improvement in 2006 over 2005. For District 11 the distribution remains the same over both years, and is strictly better than both Districts 4 and 7, mainly due to sensors that have very long runs of 1's.

The 0-runs remain the same year over year for all Districts as shown in Figure 17. District 4 exhibits a slight improvement. An interesting phenomenon is worth noting. For District 4, 61% of the 0-runs have length 1 in 2006; the corresponding numbers are 48% for District 7 and 49% for District

11. That is, many sensors experience failures that last one day. To check if such failures are the result of insufficient samples being received, we consider run plots for ND-filled sequences. Figure 18 display the results. As expected, the 1-run distributions have improved, but interestingly the 0-run distributions remain almost the same. For District 4, 42% of the 0-runs are one day long in 2006 (Figure 19). For District 7, this number is 50% and for District 11 it is 33%. This means that the underlying causes of one-day failures are not due to an insufficient number of samples, and they are concentrated on a group of sensors.

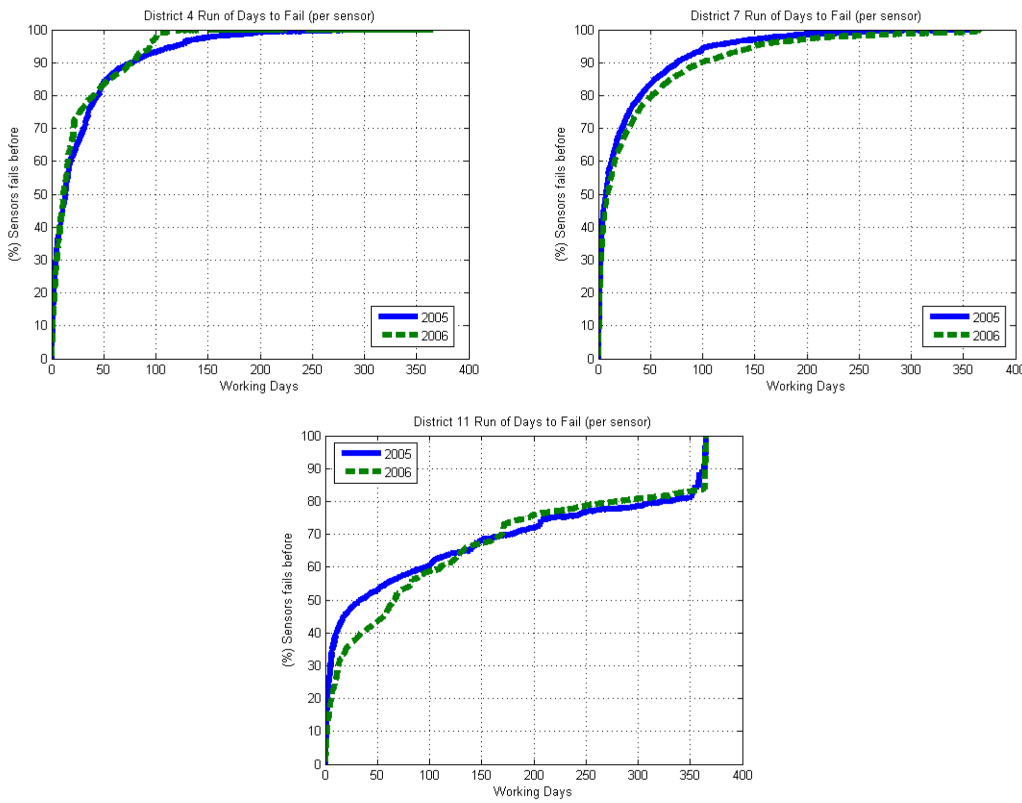


Figure 16: 1-runs distribution of District 4, 7 and 11 (2005-2006, filled)

9.2 Mean lifetime

Figure 20 shows the mean lifetime distributions for sensors in Districts 4, 7 and 11. For District 7 we observe an improvement in 2006 over 2005, with sensors taking longer to fail. For District 4, the performance is worse. For District 11 performance remains the same, with a large number of sensors never failing. District 7 also has longer average working runs than District 4, especially for sensors with average runs of more than 50 days.

The fixing time distribution curves in Figure 21 show that on average sensors remain failed for only a few days, making clear the oscillatory nature of the system. Furthermore, notice that District 11 has a distribution that has shorter fixing times than in the other districts.

We can analyze the effect of the insufficiently many samples by considering runs with ND-filled sequences. Figure 22 shows the results for lifetime. Notice how the mean time to failure per sensor is a lot better for all districts. Districts 4 and 11 perform similarly with about 60% of the sensors working for the entire period of observation. This suggests that communication failures play a major part in the failure states of sensors for Districts 4 and 11. Furthermore, the fixing time distributions

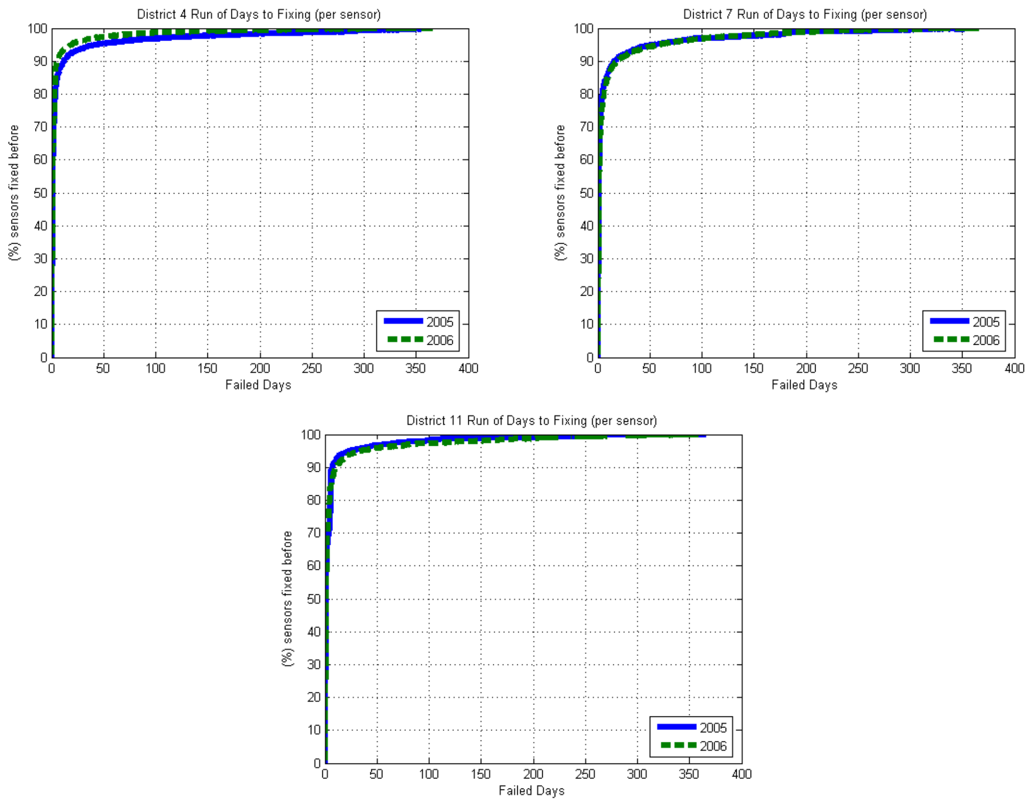


Figure 17: 0-runs distribution of Districts 4, 7 and 11 (2005-2006, filled)

(Figure 23) show that 0-runs are relatively short on average, even after insufficient sample states are filtered out. This means that the other error states do not force a sensor to be permanently broken. For District 4 there is also a shift to lower average 0-run lengths from 2005 to 2006, showing that after sensors were fixed, temporary faults other than communication failures are observed. This means that the sensor system could be essentially less reliable.

To conclude this section, Figure 24 shows the time-to-failure and time-to-fix distribution curves for District 7 disaggregated by highways in 2006. All highways have very close performance, except for I-5 for which the mean 1-runs are shorter than average and the 0-runs are longer than average. This could mean that I-5 has some underlying faults that cause the sensor to stay in the failed state much longer.

Conclusion 6 The 1-run distribution for District 11 is strictly better than for Districts 5 and 7, implying that sensors in District 11 keep working much longer before they fail. There is a large number of one-day long failures: 61% in District 11, 48% in District 4 and 49% in District 7. The one-day failures do not appear to be the result of 'insufficient number of samples' and they seem to be concentrated in a group of sensors.

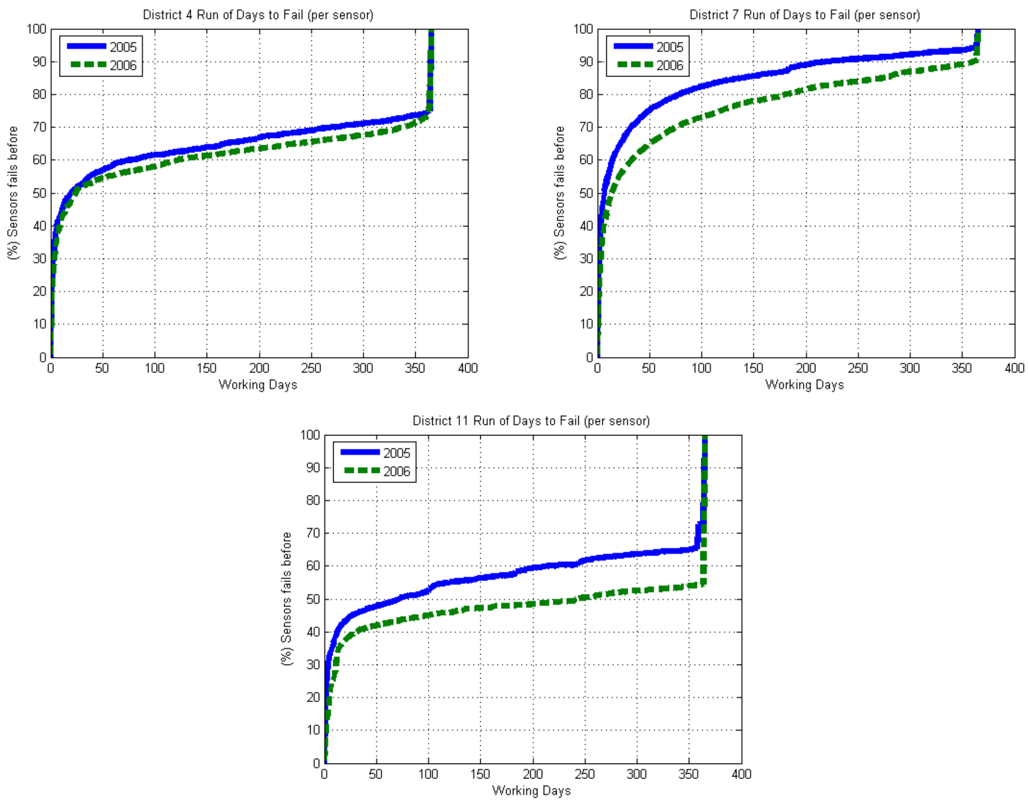


Figure 18: 1-runs distribution of Districts 4, 7 and 11 (2005-2006, ND filled)

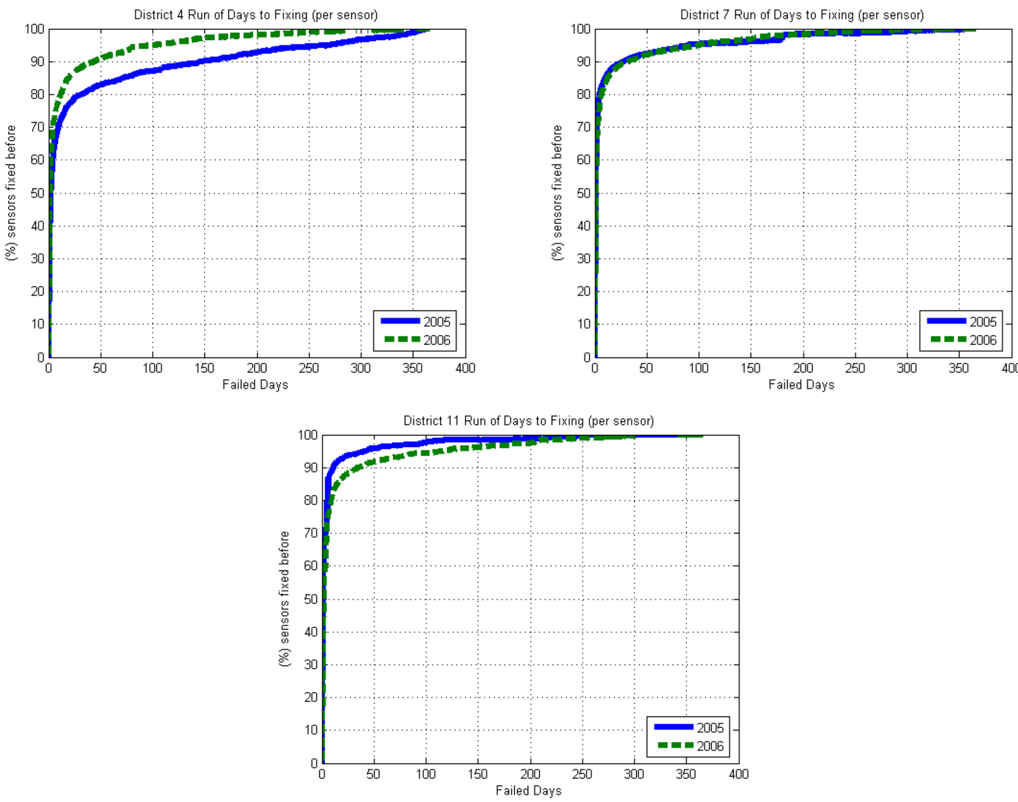


Figure 19: 0-runs distribution of Districts 4, 7 and 11 (2005-2006, ND filled)

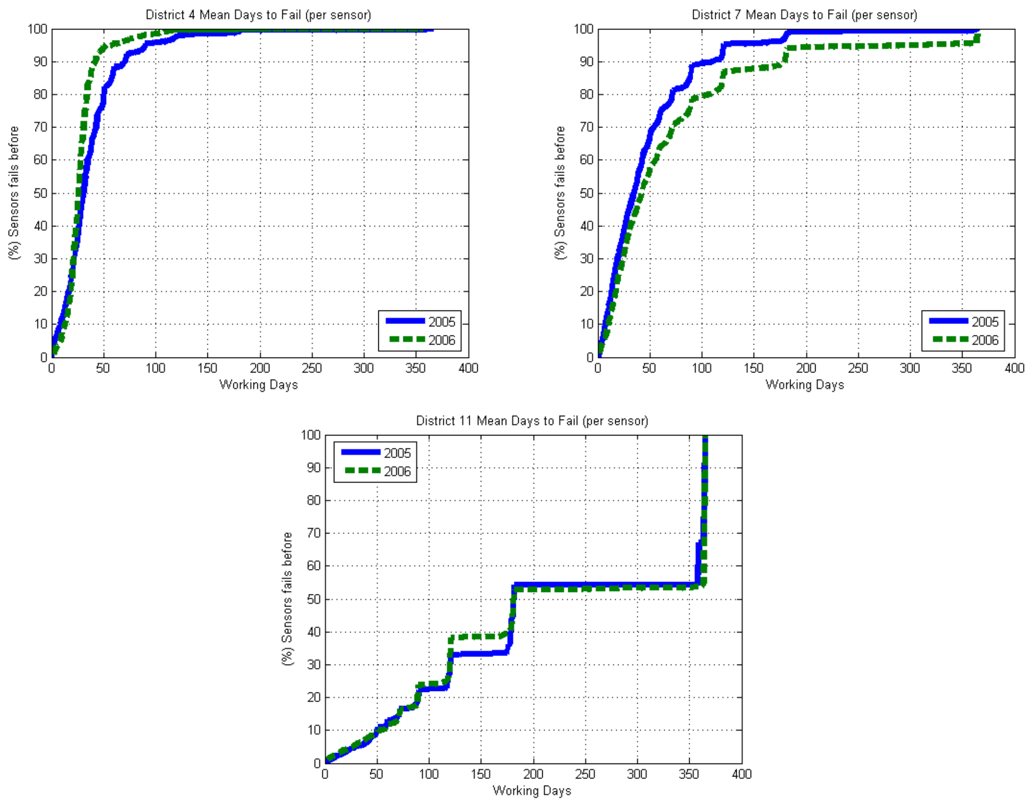


Figure 20: Sensor mean lifetime distribution of District 4, 7 and 11 (2005-2006, filled)

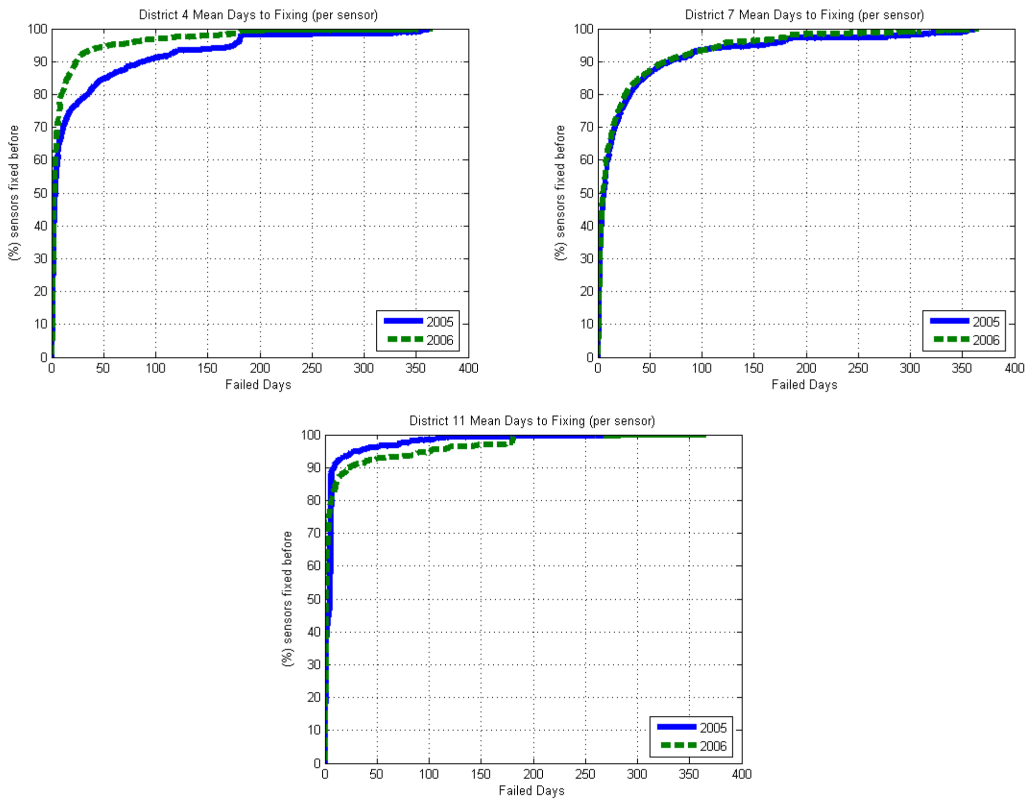


Figure 21: Sensor mean fixing time distribution of District 4, 7 and 11 (2005-2006, filled)

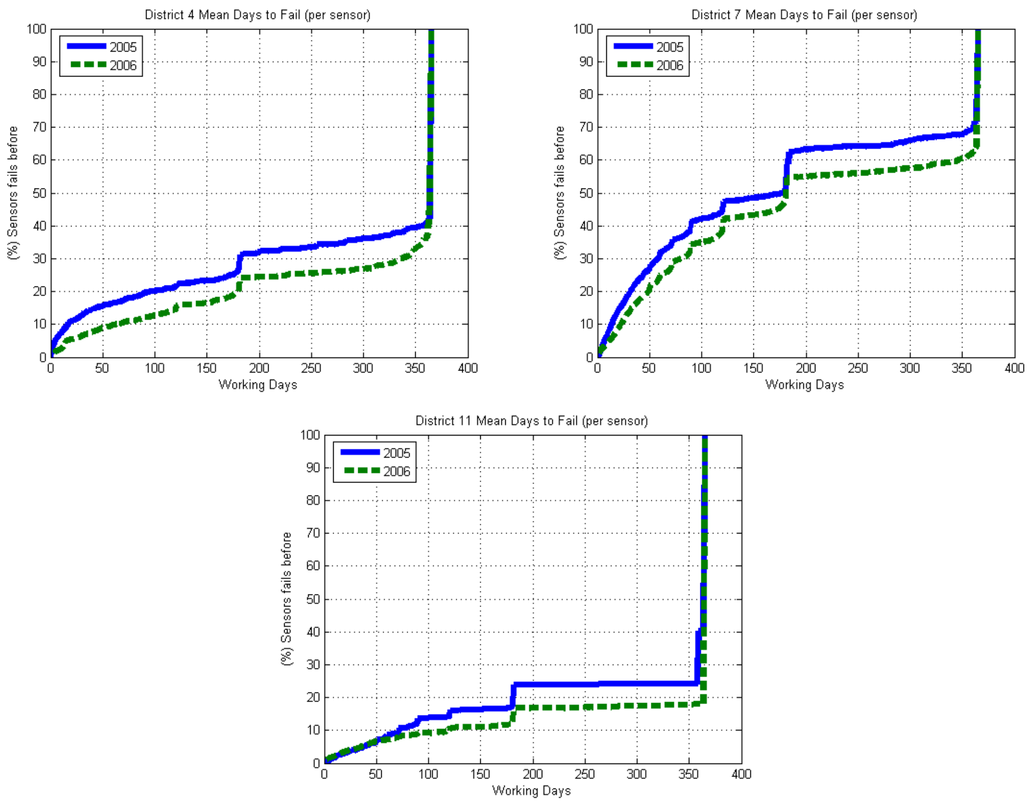


Figure 22: Sensor mean lifetime distribution of District 4, 7 and 11 (2005-2006, ND-filled)

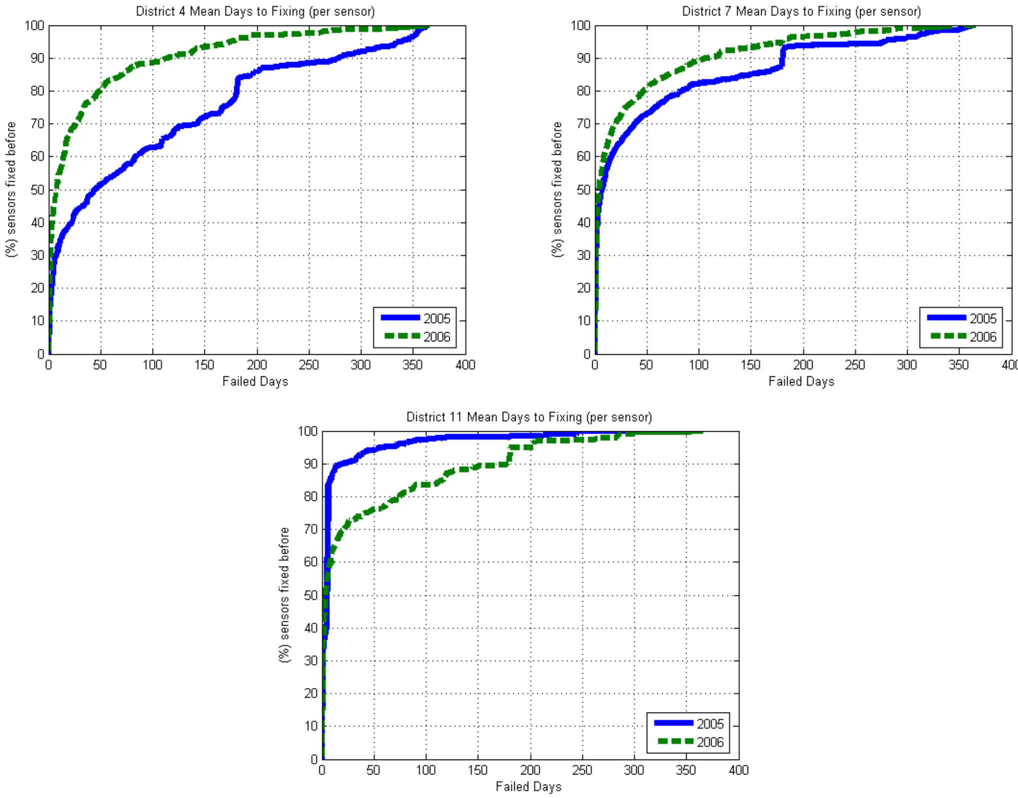


Figure 23: Sensor mean fixing time distribution of District 4, 7 and 11 (2005-2006, ND-filled)

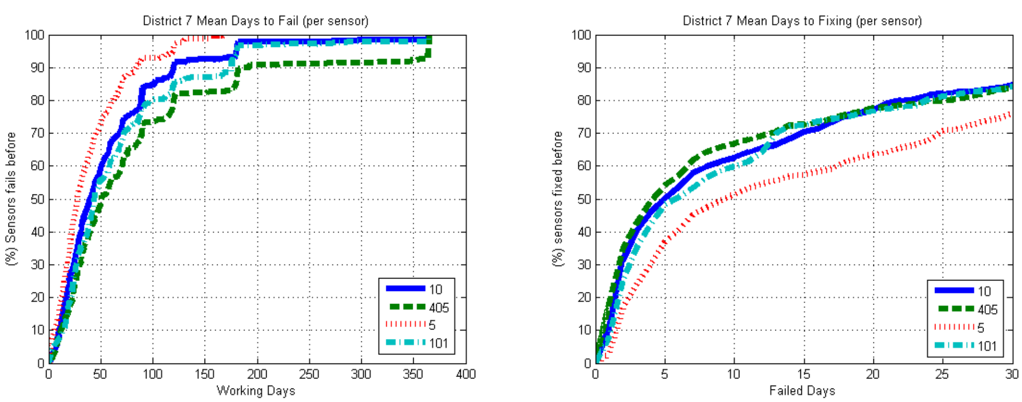


Figure 24: Sensor mean lifetime (left) and mean fixing time (right) distributions for District 7 by highway (2005-2006, filled)

10 Communication network failures

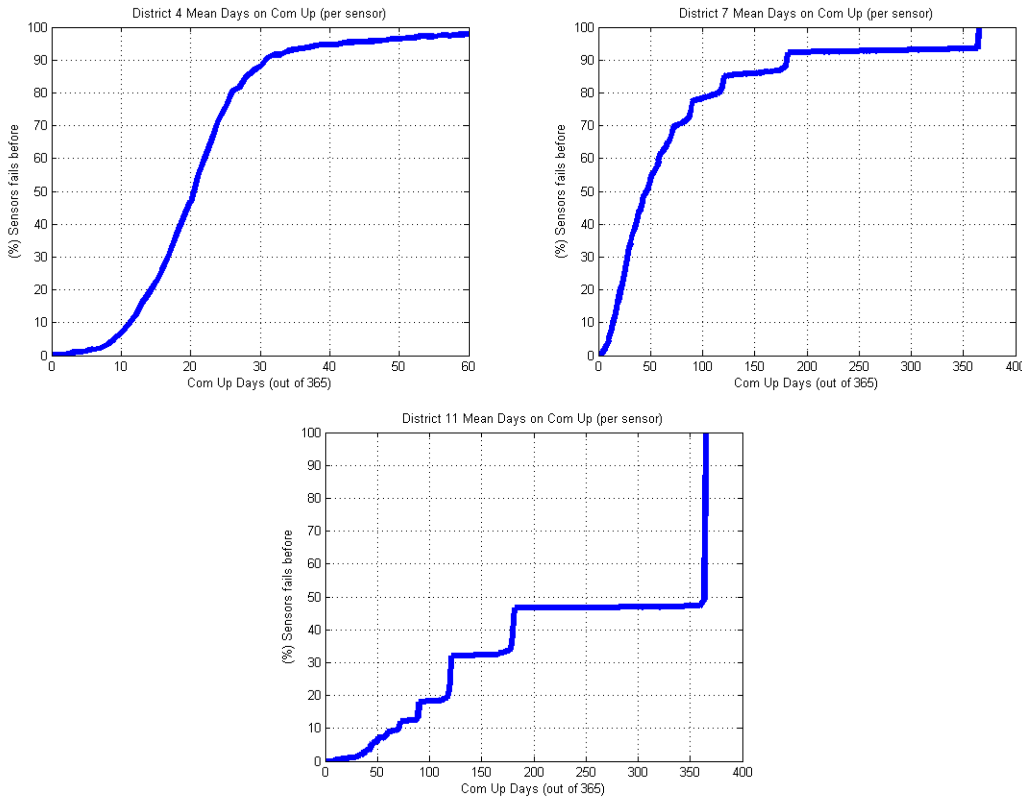


Figure 25: Mean length distribution of Comm Up period per sensor for Districts 4, 7 and 11 (2006,filled)

In this section we analyze communication network failures. For this purpose, instead of the sequence (1) or (2) we use the sequence

$$s_i^*(n) = \begin{cases} 1 & \text{if } s_i(n) \notin \{\text{No Data, Insufficient Data}\} \\ 0 & \text{if } s_i(n) \in \{\text{No Data, Insufficient Data}\} \end{cases} .$$

Thus this sequence captures failures that only relate to communication failure events. We focus on data for 2006.

First, we plot the distribution of the mean length of 1-runs, which corresponds to the average length of a communications up (Comm Up) period for each sensor. Figure 25 shows the results. We have normalized the periods with respect to the number of days a sensor was observed in an year. District 11 has the best comm up average time distribution, with 80% of the sensors having Comm Up runs of 100 days or longer. For District 4, the average Comm Up period for a sensor is less than 30 days for 90% of the sensors. For District 7, 30% of the sensors have Comm Up average run lengths of 30 days or less, and 30% of the sensors have Comm Up average periods of 100 days or more.

Next, we plot the distribution of the mean length of 0-runs, which corresponds to the average length of a communications down (Comm Down) period for each sensor, Figure 26. District 4 and District 11 have very similar behaviors. 70% of the sensors in District 4 have average Comm Down run lengths of 5 days or less. In District 11, 70% of sensors have average Comm Down run lengths of 3 days or less. District 7 has a different behavior. 50% of the sensors have an average Comm Down run length of 5 days or less and 30% have average Comm Down run lengths between 5 days and 25

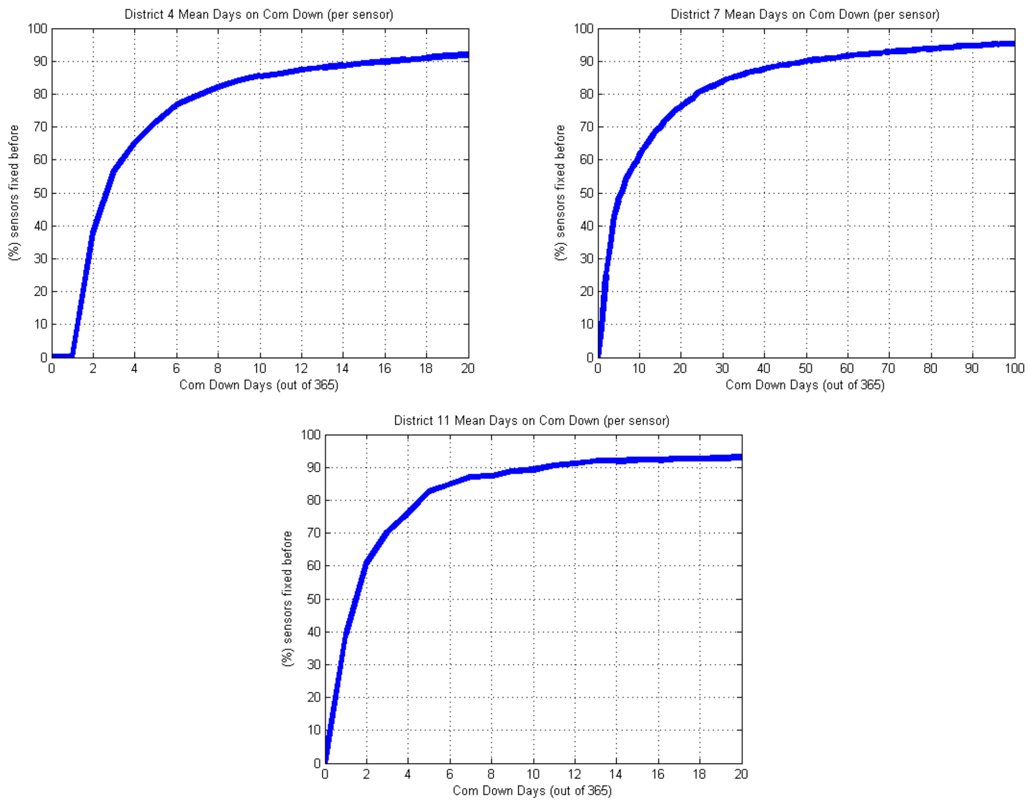


Figure 26: Mean length distribution of Comm Down period per sensor for Districts 4, 7 and 11 (2005,filled)

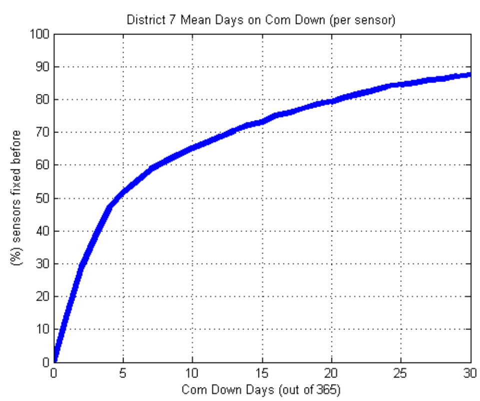


Figure 27: Mean length distribution of Comm Down period per sensor for non-filled data for District 7 (2005-2006)

days. One might suspect that this is due to the fact that District 7 added more sensors in 2006 than other Districts. However, Figure 27 shows this is not the case. Still it is interesting that the Comm Down periods lengths are short. This shows the unreliable nature of the communication network, and may be due to the communication protocol or equipment being used.

Figure 28 strengthens our conclusions by plotting the distribution of the number of 1 day failures for each sensor. Notice the huge number of number of 1 day failure events, confirming that

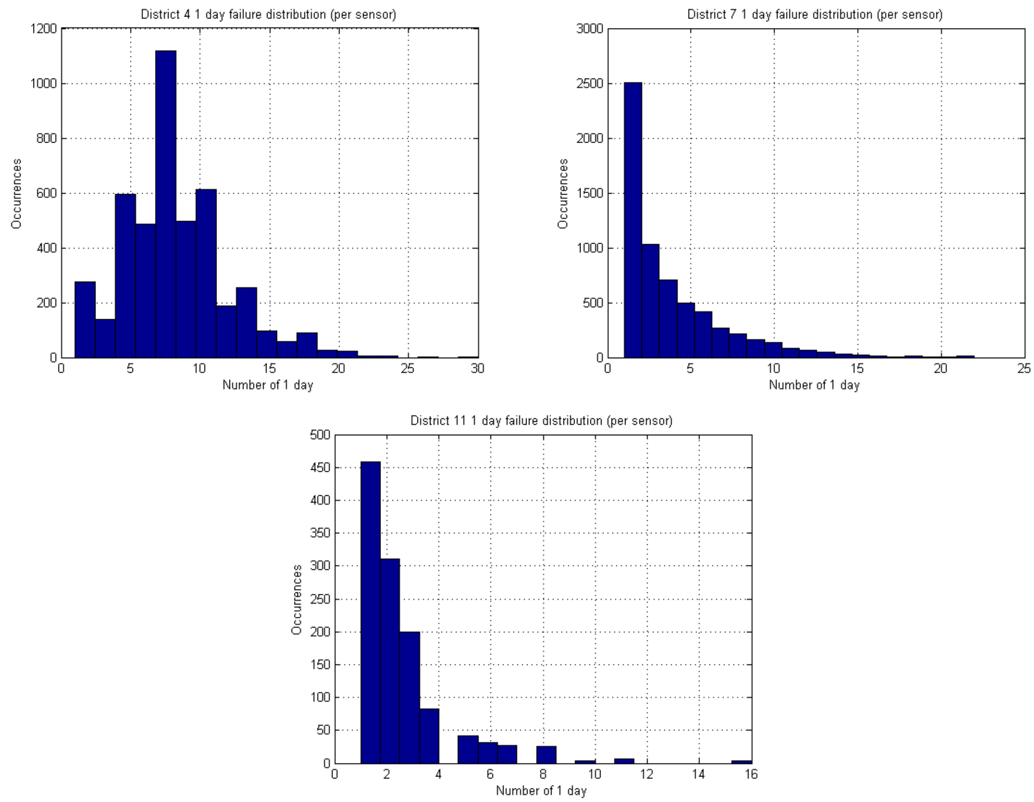


Figure 28: Distribution of number of 1 day failures for each sensor in Districts 4, 7 and 11 (2005-2006)

communications is unreliable. This holds true for all districts.

Conclusion 7 The communication networks in Districts 4 and 7 are very unreliable, compared with District 11. In District 4, communication with 90% of sensors fails within 30 days compared with 30% in District 7 and 5% in District 11. Generally communication failures have short duration. In District 4, 70% of failures last for at most five days; in District 7, 50% of failures last for at most five days; and in District 11, 70% of failures last for at most three days. The failures could be the result of a poor choice of communication protocols.

11 Link reliability

In the previous section we saw that the communication network in District 4 is very unreliable. We can quantify the reliability more directly, instead of simply using the diagnostic state classification of PeMS. We use the number of 30-sec samples actually received by PeMS from each sensor and for the District. Our non-parametric choice of estimator is again the histogram.

For this estimate we exclude days when no samples were received. Those are accounted separately. A second feature in the data is also considered. In any given day, a different number of samples may be received from each sensor. But there is also a maximum number over all sensors in the network for that given day. We observe that for some days, this maximum is consistently smaller than the theoretical maximum of 2,880 samples per day. Figure 29 shows the un-normalized histogram of

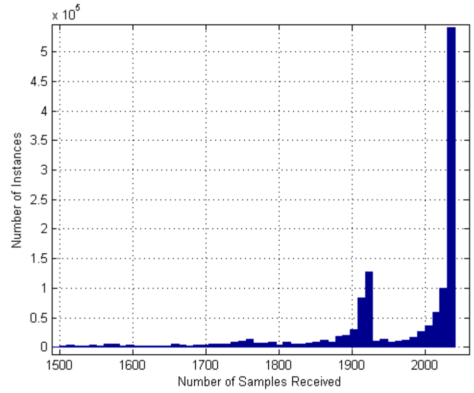


Figure 29: Distribution of maximum number of samples received for District 7 (2005-2006)

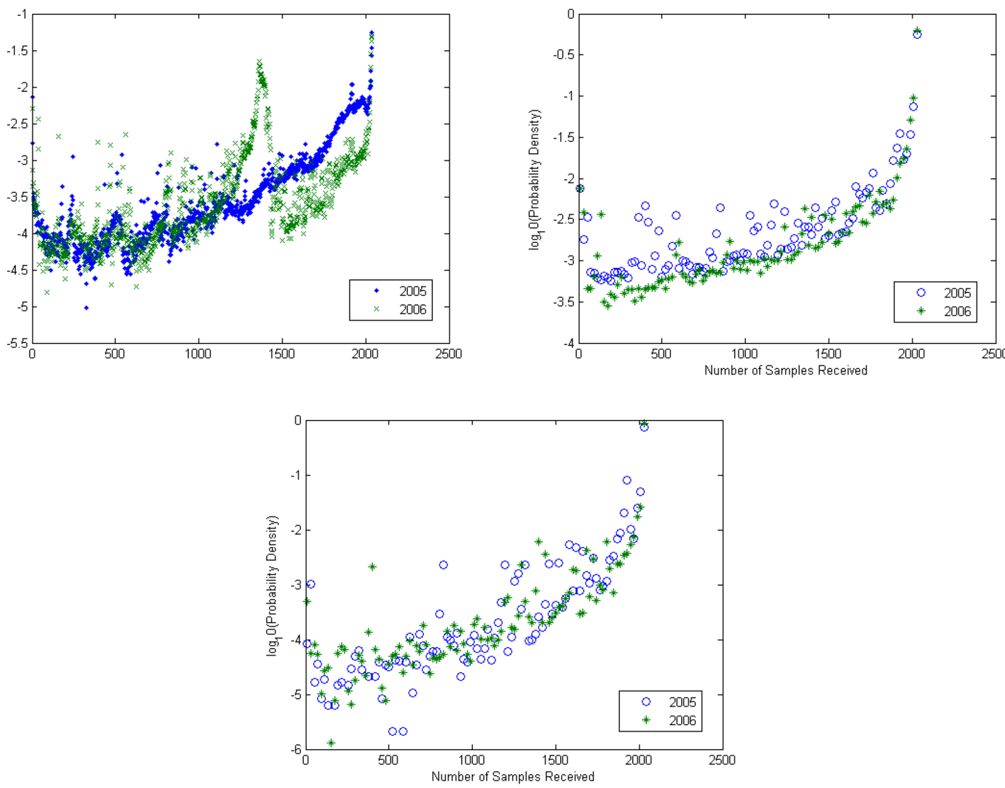


Figure 30: Normalized distribution of number of samples received for (a) District 4, (b) District 7 and (c) District 11 (2005-2006)

samples received for District 7. Notice the small repeated structure in the figure, which may indicate that some modem banks are down.

To overcome the effect of this kind of failure, we use a normalized number of samples values: for each day, we multiply the number of samples received from a sensor by a coefficient so that the maximum number received from all sensors for that day is 2,000. Results of the estimated probability densities are shown in Figures 30 and 31. In these plots, better performance is indicated by higher values towards the right end of the plot (high probability of receiving a high number of samples). Comparing

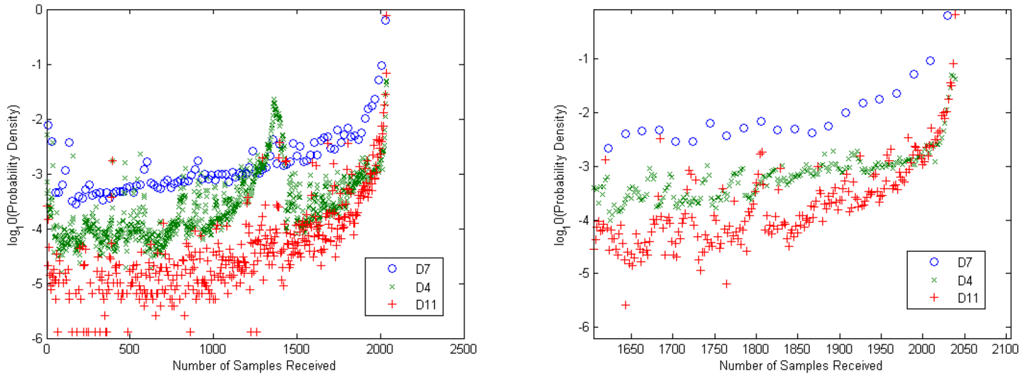


Figure 31: Comparison of normalized distribution of number of samples received (a) full view and (b) Zoom (2006)

across districts, in Figure 31, we can see that District 11 has a much better link quality than Districts 4 and 7. This accounts for the phenomenon observed in Section 5 of an increased number of **always-1** sensors, when the fault sequence considers Insufficient Samples state as a communication failure.

This analysis reinforces the conclusion of Section 10: communication network failures are both very significant and unlikely to be fixed by the Detector Fitness Program.

12 Detector Fitness Program

The Detector Fitness Program for Districts 4 and 7 is an attempt to improve the reliability of their sensor networks. The Program sent crews to fix sensors which were suspected on the basis of their PeMS diagnostic state *for a single day.* We have seen above that the sensor network in these Districts is very unstable. Hence it is a poor idea to determine the suspect list on the basis of a single day, especially if the failed state is due to a communication failure.

In this section we investigate the effectiveness of the fitness program, using the metrics developed earlier. We compute these metrics for periods before and after the visit, focusing attention on visited sensors and comparing visited and non-visited sensors.

12.1 Summary

Tables 9 and 10 summarize the effort expended in the fitness program for Districts 4 and 7. The column "fixed" is based on the reported claim that a particular sensor was fixed during the visit.

Notice that only 33% of the visited sensors in District 4 and 52% in District 7 were fixed. The number for District 7 is higher because the crew could replace the loop in some locations.

Thus the DFP records claim a 'success' rate between 30 and 50%. We will see below that this claim is illusory.

Tables 11 and 12 display a summary of the most common failure causes. The rows do not add up to 100% because some reports record multiple causes and some records report no cause. Modem, detector card issues and bad/open loop are the most common causes. The first two can be fixed by possibly replacing the equipment or resetting it, but fixing open or bad loops requires construction work. Notice also a significant number of non-operational loops: sensors with missing parts, no power, or are at locations in a construction site. Such loops may nevertheless report samples

Highway	Total Investigated	Fixed
80	441	20.4%
101	696	37.5%
680	485	31.5%
880	576	35.1%
All	3244	33.4%

Table 9: Fitness Program summary District 4.

Highway	Total Investigated	Fixed
5	638	46.1%
405	443	41.8%
10	401	45.9%
605	359	71.9%
101	238	44.1%
All	3192	51.7%

Table 10: Fitness Program Summary District 7.

depending on the configuration table and the communication network. Maintaining the configuration table should improve sensor network reliability.

Highway	Bad/Open Loops	Missing Parts	Modem/Card Issues	Under Construction	No Power	Other Issues
80	10.0%	15.0%	13.6%	7.3%	0.9%	3.6%
101	14.7%	12.9%	29.9%	1.7%	2.9%	1.3%
680	11.1%	20.8%	29.1%	12.8%	2.5%	1.2%
880	6.3%	6.9%	11.6%	2.6%	2.4%	0.7%
All	12.5%	15.1%	26.2%	5.6%	4.0%	3.7%

Table 11: Fitness Program summary of failures District 4.

Highway	Bad/Open Loops	Missing Parts	Modem/Card Issues	Under Construction	No Power	Other Issues
5	35.7%	21.8%	39.5%	10.8%	3.8%	8.3%
405	20.8%	17.4%	32.1%	23.0%	5.0%	4.5%
10	18.0%	11.0%	46.4%	1.0%	4.5%	22.7%
605	30.6%	22.3%	43.5%	1.4%	11.4%	4.2%
101	17.6%	21.0%	36.1%	3.8%	16.0%	7.6%
All	21.6%	17.3%	40.1%	7.9%	8.5%	11.6%

Table 12: Fitness Program summary of failures District 7.

12.2 always-0 sensors

Table 13 summarizes the information on **always-0** sensors that were visited. Almost 70% of the **always-0** sensors in both Districts were visited (see the total of **always-0** sensors in Table 6 for 2006). Furthermore, almost 30% of the visited sensors were in the class of **always-0** , which is only slightly less than the proportion of **always-0** in the population in Table 6. Thus our analysis of the **always-0** sensors based on DFP reports may apply to the entire population of **always-0** sensors.

Information	District 4	District 7
always-0 visited	65%	68%
visited that are **always-0**	27%	30%
total sensors that are **always-0**	25%	16%

Table 13: Fitness Program Summary for visited **always-0** sensors (867 visited sensors for District 4, 958 for District 7)

The effectiveness of the visits to **always-0** sensors can be seen in Tables 14 and 15. Only 9% of the **always-0** sensors were claimed fixed. Most of the **always-0** sensors that were *not* fixed were because of ‘Bad or No Equipment’,‘Non-existing lanes’, or ‘Open/bad loops’.

Type of always-0	Number of Sensors	(%)
Fixed	73	**8.5**%
Bad or No Equipment	370	42.7%
Open or bad loops	193	22.2%
Lane not existent	73	8.5%
No Power	28	3.2%
Other	130	15%
Total Visited	867	100.0%

Table 14: Fitness Program Summary for District 4, **always-0** sensors

Type of always-0	Number of Sensors	(%)
Fixed	84	**8.8**%
Open or bad loops	249	25.9%
Bad or No Equipment	142	14.8%
Lane not existent	137	14.3%
No Power	86	9.0%
Other	260	27.0%
Total Visited	958	100.0%

Table 15: Fitness Program Summary for District 7, **always-0** sensors

One important question is what happens to the 9% of **always-0** sensors that were claimed fixed. Do any one of them return to being **always-0** ? For this purpose we check if any of the fixed sensors return to an **always-0** state after the reported visit date. Instead of requiring that all samples after the fixing date be zero (until March 2007), we require that at least 89 days out of 90 have reported zeros (we relax our condition as some sensors have been observed for a smaller number of days after fixing).

The results are shown in Table 16. Notice that in District 4, about 40% of the sensors revert back to the **always-0** state, although some sort of fixing was done. For District 7, this is the case for 24% of the sensors. If this information is taken into account, only 44 **always-0** sensors in District 4 (5% of visited **always-0** sensors) and 64 in District 7 (7% of visited **always-0** sensors) were effectively fixed. Thus the actual success rate of DFP visits to **always-0** sensors is only about 5%.

District	Claimed fixed	Continued **always-0**	(%)
District 4	73	29	40%
District 7	84	20	24%

Table 16: Fitness Program Summary for District 4, District 7, **always-0** sensors

12.3 Productivity and stability

Figure 32 shows the productivity of Districts 4 and 7 for *all* visited sensors before and after being visited. For both districts the productivity curve indicates an improvement. However the improvement in stability is insignificant in both Districts (Figure 33). This confirms our earlier conclusion that communication network failure is an “independent” failure, which the DFP does not effectively address.

To evaluate further the productivity improvement, we investigate the performance of sensors that were visited but *not* claimed to be fixed (Figure 34). Notice that after the visit, there is a slight performance improvement in both Districts. This could be result of misreporting the effects of

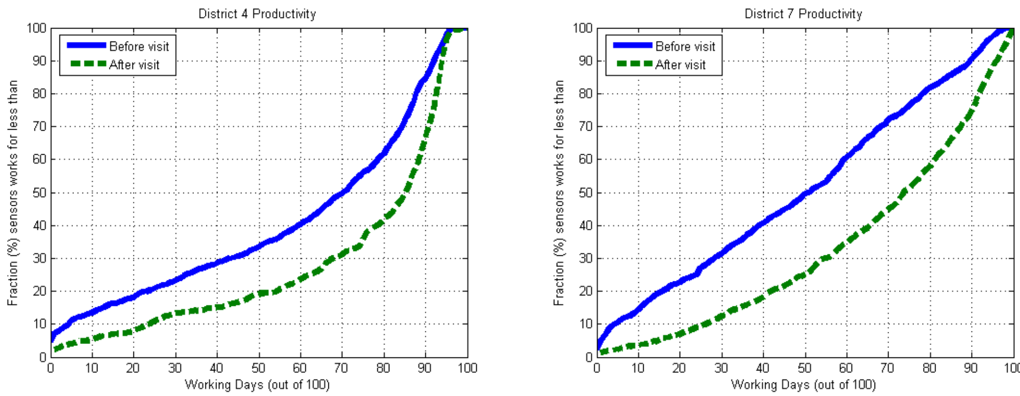


Figure 32: Productivity of visited sensors in District 4 (left) and District 7 (right) before and after visit (2005-2007)

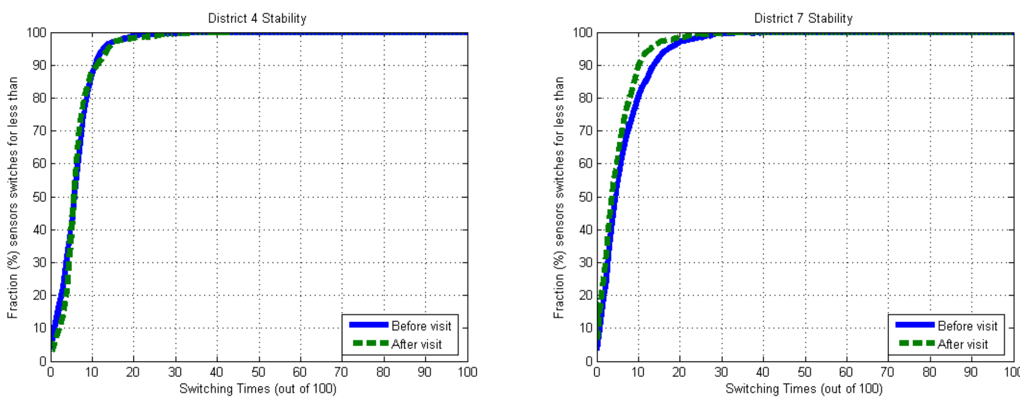


Figure 33: Stability of visited sensors in District 4 (left) and District 7 (right) before and after visit (2005-2007)

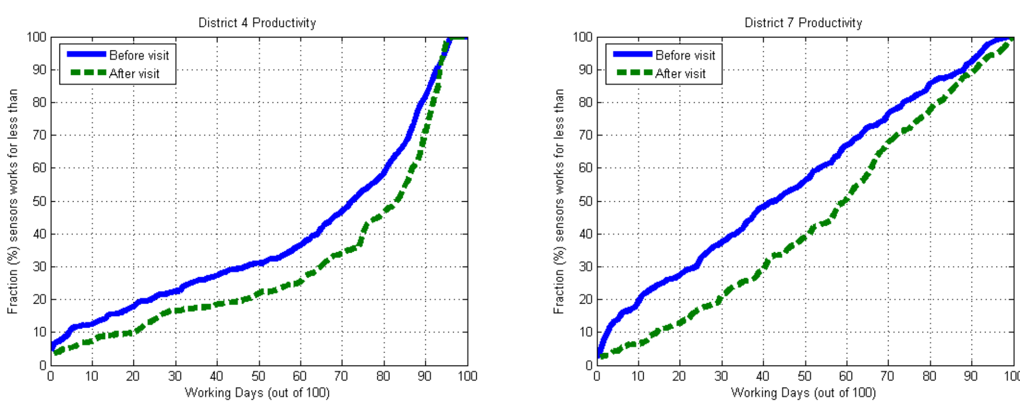


Figure 34: Productivity of visited but **not** fixed sensors in District 4 (left) and District 7 (right) before and after visit (2005-2007)

fixing. It could also be the case that on the day the list of suspect sensors was compiled, these sensor had failed but spontaneously recovered later as frequently happens. Again notice that the stability (Figure 35) remains the same, and the curves are very close to yearly estimates.

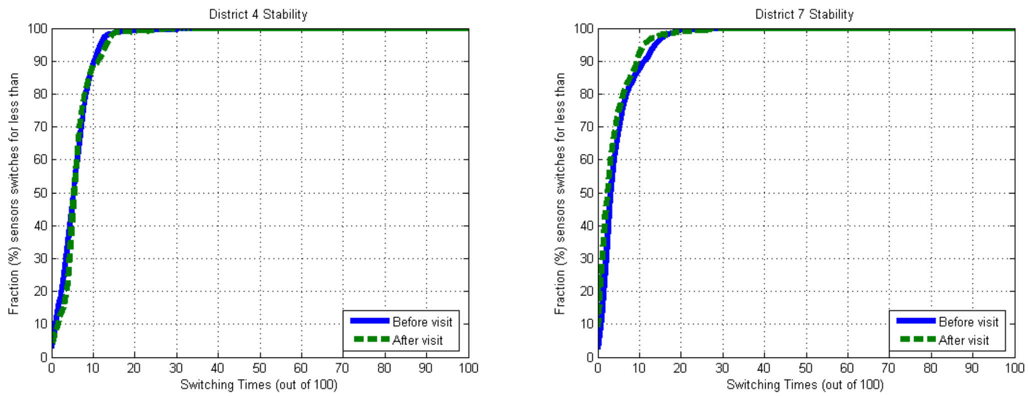


Figure 35: Stability of visited but **not** fixed sensors in District 4 (left) and District 7 (right) before and after visit (2005-2007)

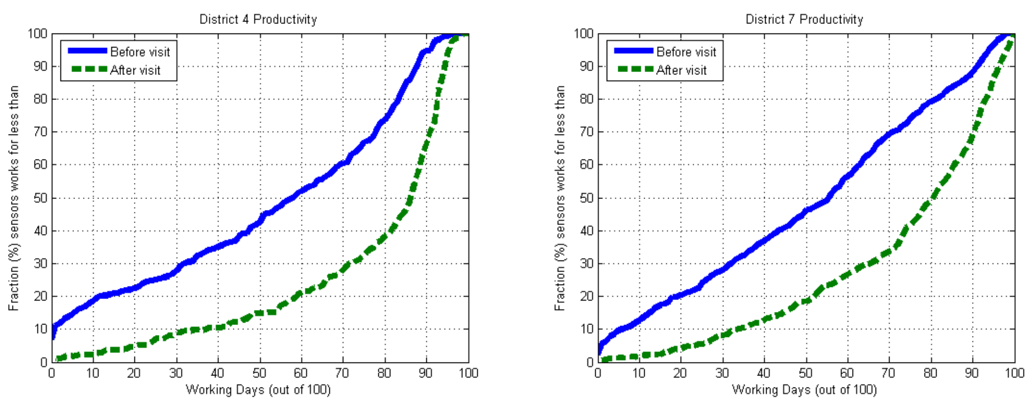


Figure 36: Productivity of visited and fixed sensors in Districts 4 and 7 before and after visit (2005-2007)

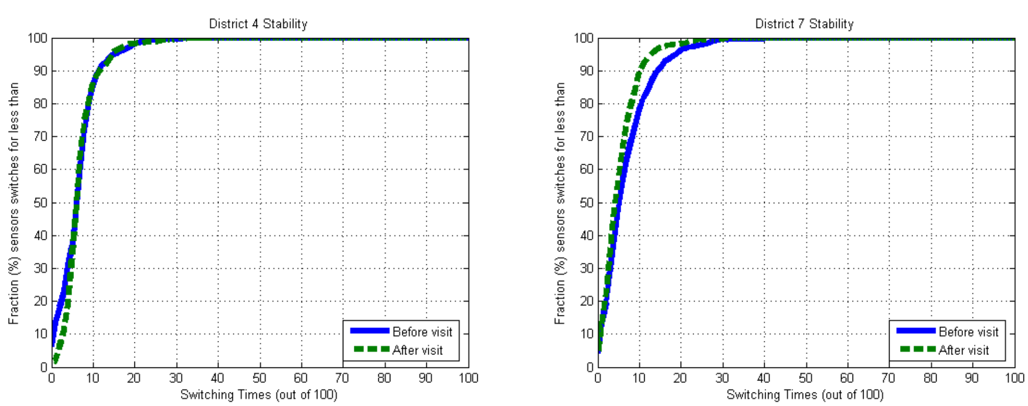


Figure 37: Stability of visited and fixed sensors in Districts 4 and 7 before and after visit (2005-2007)

Figure 36 shows the productivity estimates for sensors that were visited and claimed fixed. In this case there is a very significant improvement in performance, confirming that the Detector Fitness Program has an effect in system performance. The productivity of these sensors is now the same as for the District as a whole (compare with 9).

On the other hand, the stability shows no improvement (Figure 37), again implying the independence of communications failures and their immunity to the DFP.

To conclude this section Figures 38 and 39 show productivity estimates for visited sensors with different classes of failures. Notice that the highest improvement obtains for sensors that had missing equipment or modem/card problems. Fixing crews made more difference to these failure classes. Unfortunately, in the absence of remote diagnosis, one cannot tell whether a sensor has failed because of these causes.

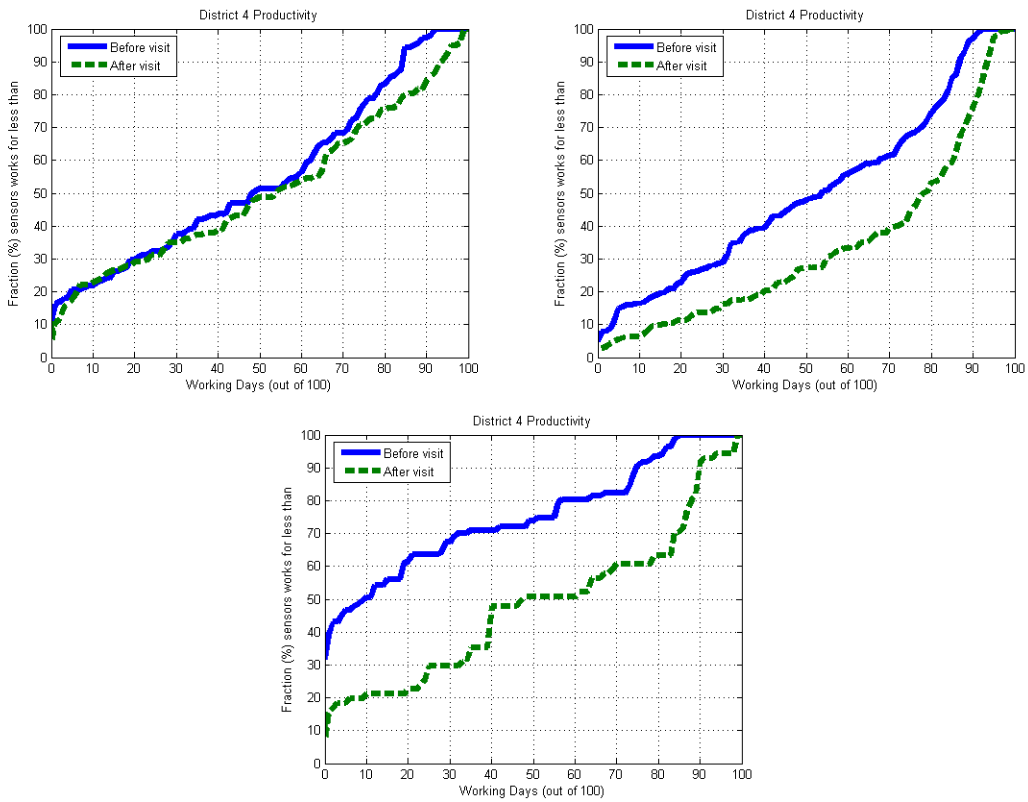


Figure 38: Productivity of visited sensors in District 4 with observed failures: Open loop, Modem issues and Missing equipment before and after visit (2005-2007)

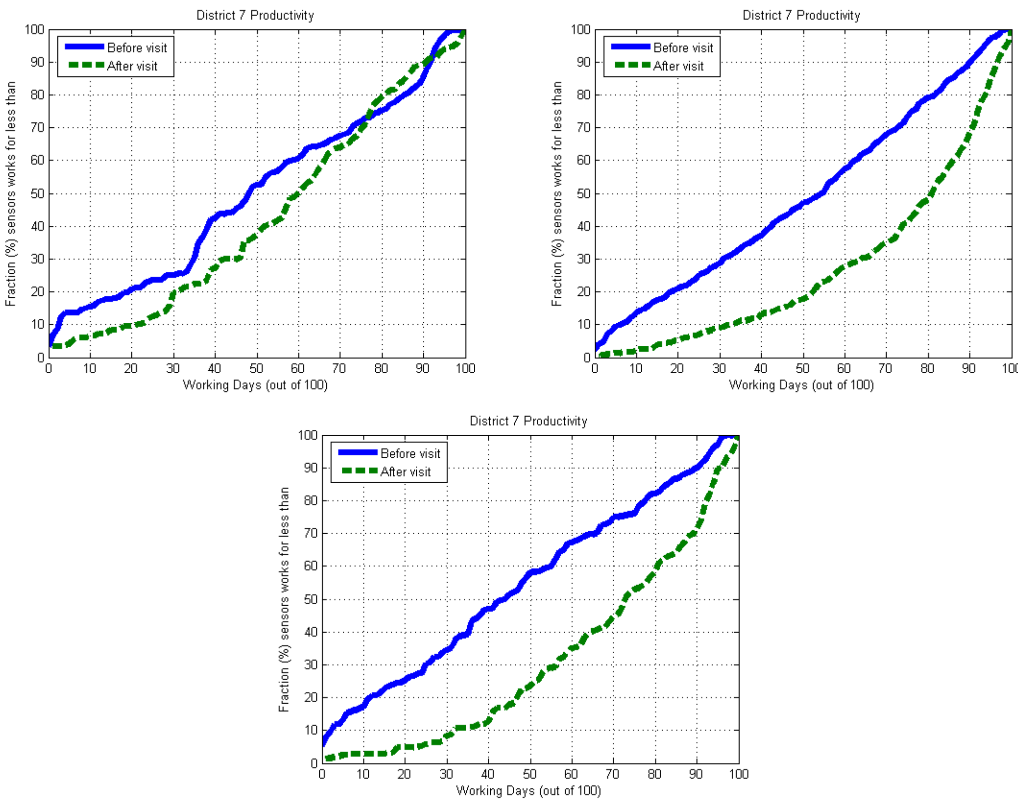


Figure 39: Productivity of visited sensors in District 7 with observed failures: Open loop, Modem issues and Missing equipment before and after visit (2005-2007)

12.4 Lifetime and fixing Time

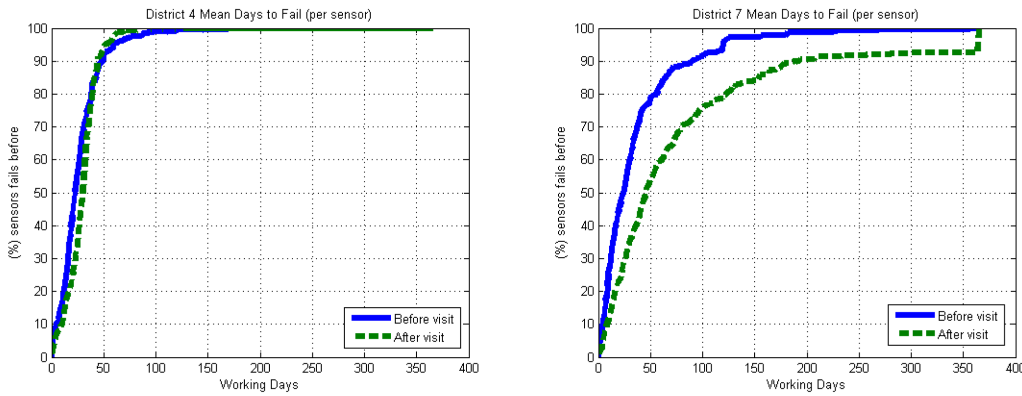


Figure 40: Lifetime distribution of visited and **not fixed** sensors in Districts 4 7 before and after visit (2005-2007)

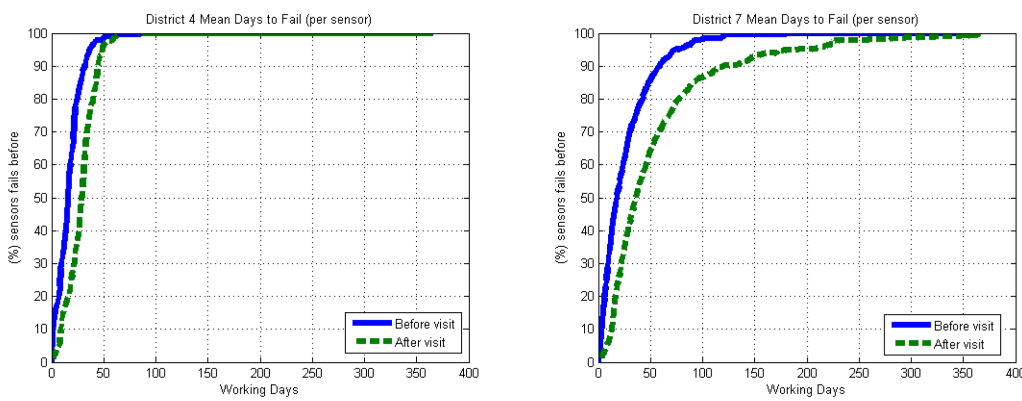


Figure 41: Lifetime distribution of visited and **fixed** sensors in Districts 4 7 before and after visit (2005-2007)

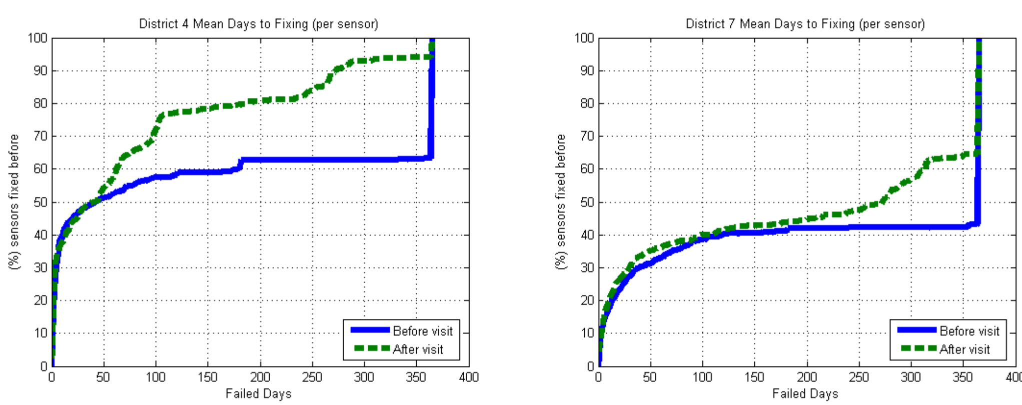


Figure 42: Time to fix distribution of visited and not fixed sensors in Districts 4 7 before and after visit (2005-2007)

In this subsection we investigate the improvement to lifetime resulting from the Detector Fitness

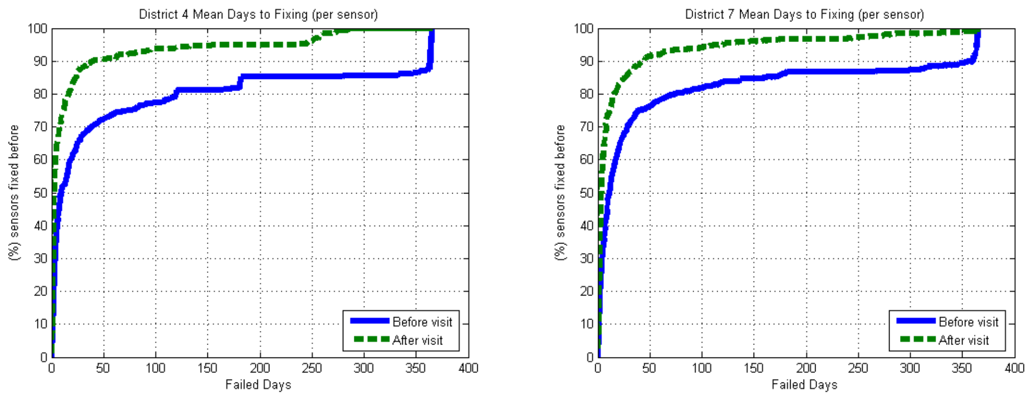


Figure 43: Time to fix distribution of visited and fixed sensors in Districts 4 and 7 before and after visit (2005-2007)

Program. Interestingly, the 1-runs of a sensor are deeply affected by communication failures, and thus we will see that the improvement obtained in the average time to failure for each sensor is not as much as seen in productivity. To improve lifetime one needs to improve both key metrics: productivity and stability. This concept is verified with our data.

Figures 40 and 41 show the average per sensor lifetime curves for both districts for visited sensors that were not fixed and those that were fixed, respectively. Notice that for sensors that were not fixed, there is no improvement for District 4, and some improvement for District 7. This implies that the average behavior improved for District 7 without any direct intervention on the sensors (result of statistical variation). Fixed sensors improved their average length of 1-runs for Districts 4 and 7. Still the improvement is not as remarkable as the improvements observed in productivity. Notice that for District 7, the after visit curve of fixed sensors is slightly worse than for non-fixed sensors. For example, for fixed sensors, 15% of the sensors work continuously for an average of more than 100 days. The same number for non-fixed sensors is 25% for an average of more than 100 days.

The average time to fixing distributions in Figures 42 and 43 show some improvement as well. For District 7 we see a reduction on the average 0-run length. This evidence supports the thesis that inherent failures in the sensors show longer 0-run lengths, whereas communication failures cause short (mostly 1 or 2 day long) 0-run lengths. It is interesting to observe also that for sensors that were not fixed, there is a large number of **always-0** sensors which we chose to plot in these figures (they show up as sensors that are never fixed).

Conclusion 8 DFP reports claim that between 30% and 50% of visited sensors were fixed. The actual success rate is much lower. Nearly 30% of the visits were to **always-0** sensors, only 5% of which were fixed. The productivity of sensors that were visited and fixed improved to match the average for the District. Stability showed no improvement. The most improvement came from visits to sensors whose observed failures were due to modem issues or missing equipment.

13 Conclusions

In this report we performed a systematic analysis of failures and the actions taken against them in 2 districts in California. Our analysis did not rely in any specific parametric models, avoiding any particular assumptions about the sensor behavior. Instead we devised simple metrics that can be easily computed for very large systems to tackle the problem. Another innovation was the use of a whole day (or block) of samples to attribute a sensor state. In other problems, maybe a day might be a block too long, but for transportation networks, a day of missing samples can be reasonably interpolated.

We group our conclusions under three headings: methodology, district performance, and Detector Fitness Program.

Methodology

These conclusions relate to the methodology we have followed.

- **always-0** sensors should always be treated separately as they represent a clearly different class of behavior than other sensors.
- Productivity and Stability capture independent aspects of the system performance. A system's productivity can be improved without affecting its stability.
- Productivity captures the underlying sensor system performance and Stability capture communication network performance. The latter is related to the choice of communication technology.
- Highly productive systems could still have poor Lifetime (or runs distribution). The average 1-run length in a sensor is a good metric of uptime. Its average 0-run length allows us to infer more about the underlying cause of instability. Short average 0-runs usually indicates a poorly functioning communication network.
- Metrics should be normalized to account for the number of days in operation in order to provide meaningful insights into the system. Although this seems a minor detail, it greatly improves our understanding of plots.
- The simple way we treated missing data - which in this case corresponded to days where communication failed (No Data) and/or there were insufficient samples to make a daily decision - was to use the previous day's state. This worked well as we got many insights by comparing the inclusion and exclusion of Insufficient Samples state as a com fault. In a more parametric setting, maximum likelihood estimators can be used to estimate parameters even with missing values, but the estimation complexity becomes a lot higher, which might be an issue if huge volumes of data are to be addressed.
- The scope chart allows an easy visual comparison of the performance over time. It also captures the same information available by plotting the number of samples acquired, but it is visually much less burdensome. Less information displayed does not necessarily mean less information.
- The number of samples received can be used to estimate link quality metrics, such as the probability of receiving a particular number of samples. Link quality is almost exclusively a metric of the communication network.
- Communication failures can be studied just like other types of failure, by considering an alternate sequence where the only fault is a communication fault, and the remaining states are "Good" states. The same metrics apply.

- When failures are fixed or repaired, performance evaluation after the fact should be done over collections of samples, not just based on a single day observation, as sensor systems can be unstable. The metrics proposed in this report capture such improvements accurately.
- Fixing actions should take into account the possible classes of failures the sensor experience, as the effectiveness of fixing can be very different in different classes.
- It is essentially to have proper bookkeeping of maintenance data, with a repeatable (instead of an ad-hoc) reporting system. Even when the maintenance records are not so good, the use of automated parsing and other techniques can make the data useful.

District performance

These are the main conclusions regarding of District performance based on PeMS data.

- District 11 has much better performance than District 7 whose performance is slightly better than District 4.
- Large discrepancies in the percentage of Good sensors among Districts are caused mainly by permanently failed (**always-0**) sensors.
- Systemwide oscillations in the percentage of failed sensors are caused by instabilities in the communication network, which can "black out" large sections of a District.
- Lanes that experience more intense traffic of heavy vehicles seem to have more **always-0** sensors, but on the other metrics, lane is not an influence.
- The highway variable also does not seem to play an important part in determining the productivity, stability and lifetime of sensors.
- Communication technology choice appears to be a huge variable in determining stability.
- No District's stability improved after the DFP. All three districts exhibit almost the same stability pattern, with District 4 being slightly worse than others.
- Communication link quality is better for District 11 than for District 7, which in turn is better than District 4. Nevertheless, in all Districts, significantly many samples are lost and affect the data collection. Sensors in all Districts experience a large number of one-day long communication failures.

Detector Fitness Program

- Determining which sensors to visit based on a single day of observation is not a good choice.
- **always-0** sensors experience a very low success rate, and should be low on the priority of the fixing program.
- A considerable percentage of **always-0** sensors that are claimed to be fixed, in fact never work.
- Productivity improves after fixing, but stability does not.
- Modem/Card issues and no equipment problems are the failure causes that most benefit from fixing, whereas Open Loop failures cannot be significantly repaired. This could be because only a very small fraction of Open Loop sensors are actually fixed.
- Fixed sensors in Districts 4 and 7 exhibit almost the same productivity pattern, possibly implying fixing crew performance was consistent across districts.
- District 4 has poorer DFP records than District 7.

14 Acknowledgement

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Appendix

A System metrics and sensor Markov models

Consider a two-state Markov chain with states labeled $\{0, 1\}$. The transition probabilities between states are labeled p_{01} for transitions from state 0 to 1 and p_{10} for the opposite transition. We identify state 0 with a failed state of a sensor, and state 1 with a working state. The stationary distribution is denoted by π, with elements π_0 and π_1 corresponding to states 0 and 1. In this section we show how the productivity and stability metrics introduced in Sections 7 and 8 relate to the Markov model.

Suppose the Markov chain is stationary. Let the state of the chain at time n be denoted by X_n. Then the individual productivity estimate w for a time horizon T is given by

$$w_T = \sum_{n=1}^{T} \mathbb{1}(X_n = 1). \tag{11}$$

We can compute the expectation this random variable as

$$\begin{aligned} \frac{1}{T}\mathbb{E}[w_T] &= \frac{1}{T}\sum_{n=1}^{T} \mathbb{E}[\mathbb{1}(X_n = 1)] \\ &= \frac{1}{T}\sum_{n=1}^{T} \mathbb{P}(X_n = 1) \\ &= \frac{1}{T}\sum_{n=1}^{T} \pi_1 \\ &= \pi_1 \end{aligned} \tag{12}$$

Standard results from the theory of Markov chain show that $\lim_{T\to\infty} \frac{1}{T} w_T = \pi_1$ almost surely. Similarly, for stability we have,

$$s_T = \sum_{n=1}^{T} \mathbb{1}(X_n \neq X_{n-1}) \tag{13}$$

Computing the expectation and noting that for a Markov Chain

$$\begin{aligned} \mathbb{P}(X_n \neq X_{n-1}) &= \mathbb{P}(X_n = 1 | X_{n-1} = 0)\mathbb{P}(X_{n-1} = 0) + \mathbb{P}(X_n = 0 | X_{n-1} = 1)\mathbb{P}(X_{n-1} = 1) \\ &= p_{01}\pi_0 + p_{10}\pi_1, \end{aligned} \tag{14}$$

we have

$$\lim_{T\to\infty} \frac{1}{T} s_T = p_{01}\pi_0 + p_{10}\pi_1 \tag{15}$$

Furthermore, using the relations

$$\pi_0 = \frac{p_{10}}{p_{10} + p_{01}}, \quad \pi_1 = \frac{p_{01}}{p_{10} + p_{01}} \tag{16}$$

We can thus express stability and productivity in terms of the unknowns of the model.

B Detector Fitness Program data sheets

In this appendix we present a few examples of the data obtained from the detector fitness program. See Figures 44, 46, 47 and 48. The sheets don't have a clear pattern. Furthermore, in some cases it is not clearly reported if a sensor was fixed or not (the default was assumed to be not fixed, but a machine interpretation was done based on the remaining text). Also notice that in some cases, the entries are mangled up, with actions and causes entered in incompatible columns.

C Disabled sensors for District 4

An analysis of the number of sensors in District 4 shows a discrepancy between those reported in Table 2 in section 4 and those in the PeMS website. In this we explain the differences.

Table 17 shows the sensors that reported any data for each quarter, and during 2005 and 2006. The table indicates that sensors have been added and disabled in the system. Sensors that are disabled do not report any data from the date they are disabled. In our earlier analysis, disabled sensors were not counted after the period they were disabled. Sensors enabled for any part of a year, that reported data on that year, are accounted for in the statistics of that year.

Period	Sensors	(%) Total
Q1 (2005)	4809	83.2%
Q2 (2005)	4848	83.9%
Q3 (2005)	4857	84.0%
Q4 (2005)	4912	84.9%
2005	5140	88.9%
Q1 (2006)	4895	84.7%
Q2 (2006)	4110	71.1%
Q3 (2006)	4236	73.3%
Q4 (2006)	4515	78.1%
2006	5271	91.2%
Q1 (2007)	4633	80.1%
Total	5782	100.0%

Table 17: Number of sensors reporting data in District 4.

Table 18 shows the number of sensors added and disabled for each year. Notice the large number of disabled sensors. We investigated if sensor added were replacing existing disabled sensors, but this did not seem to be the case. In fact, 6 sensors were disabled twice, meaning they were disabled, enabled and then disabled again remaining in a disabled state. We can explore further the characteristics of disabled sensors.

Period	Sensors added	Sensors disabled
2005	331	228
2006	584	982
2007 (Q1)	160	42
Total	1075	1252

Table 18: Number of sensors added and disabled in District 4.

First to make clear the connection between sensors reporting data, and disabled sensors during a period, we compare the numbers reported by PeMS and the number of disabled sensors during each quarter (Table 19). Notice that the difference between the number of data reporting sensors, and the PeMS reported sensors is exactly the number of sensors disabled in a given period.

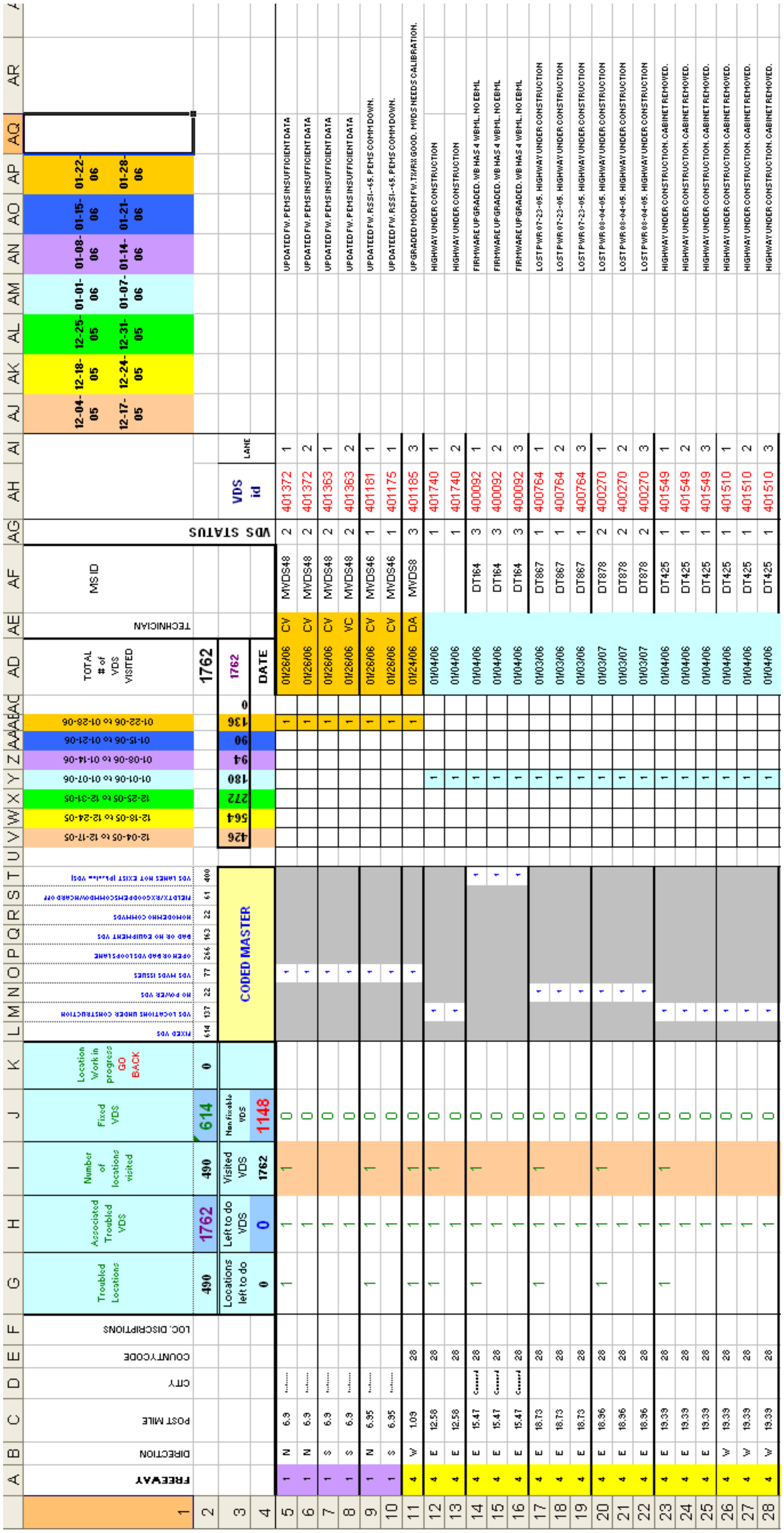
1151 of the 1252 disabled sensors correspond to complete Detector Stations being disabled (as opposed to an individual sensor being disabled). Furthermore, 890 of the disabled sensors were visited, with 231 of the sensors reported ones after the visit. 101 of the sensors were claimed fixed.

Period	PeMS	Disabled	Data reporting
Q1 (2005)	4670	139	4809
Q2 (2005)	4834	14	4848
Q3 (2005)	4782	75	4857
Q4 (2005)	4787	125	4912
Q1 (2006)	4082	813	4895
Q2 (2006)	4090	20	4110
Q3 (2006)	4212	24	4236
Q4 (2006)	4515	42	4515

Table 19: Comparing PeMS, sensors reporting data and disabled sensors District 4.

Interestingly, 554 of the 890 visited, had missing equipment, no power or were under construction, thus corresponding to sites where there could be missing sensors.

The consequences of disabling are that for periods after disabling, the sensor is accounted for in the **always-0** category. In aggregate analysis, if a sensor was disabled in 2005, it will show in **always-0** only in 2006, as during 2005 the sensor reported data for a period of time before disabling. Of course all statistics are normalized by the period of time in 2006 the sensor was enabled.



Row	FREEWAY	DIRECTION	POST MILE	COUNTY CODE	Troubled Locations	Associated Troubled VDS	Number of locations visited	Fixed VDS	DATE	TECHNICIAN	MS ID	VDS STATUS	VDS id	LANE	AR
5	1	N	6.9		1	1	1	0	01/26/06	CV	MVDS48	2	401372	1	UPDATED FW. PEMS INSUFFICIENT DATA
6	1	N	6.9			1		0	01/26/06	CV	MVDS48	2	401372	2	UPDATED FW. PEMS INSUFFICIENT DATA
7	1	S	6.9			1		0	01/26/06	CV	MVDS48	2	401363	1	UPDATED FW. PEMS INSUFFICIENT DATA
8	1	S	6.9			1		0	01/26/06	VC	MVDS48	2	401363	2	UPDATED FW. PEMS INSUFFICIENT DATA
9	1	N	6.95		1	1	1	0	01/26/06	CV	MVDS46	1	401181	1	UPDATEED FW. RSSI--65. PEMS COMM DOWN.
10	1	S	6.95			1		0	01/26/06	CV	MVDS46	1	401175	1	UPDATEED FW. RSSI--65. PEMS COMM DOWN.
11	4	W	1.09	28	1	1	1	0	01/24/06	DA	MVDS8	3	401185	3	UPGRADED MODEM FW. TX/RX GOOD. MVDS NEEDS CALIBRATION.
12	4	E	12.58	28	1	1	1	0	01/04/06			1	401740	1	HIGHWAY UNDER CONSTRUCTION
13	4	E	12.58	28		1		0	01/04/06			1	401740	2	HIGHWAY UNDER CONSTRUCTION
14	4	E	15.47	28	1	1	1	0	01/04/06		DT164	3	400092	1	FIRMWARE UPGRADED. WB HAS 4 WBML. NO EBML
15	4	E	15.47	28		1		0	01/04/06		DT164	3	400092	2	FIRMWARE UPGRADED. WB HAS 4 WBML. NO EBML
16	4	E	15.47	28		1		0	01/04/06		DT164	3	400092	3	FIRMWARE UPGRADED. WB HAS 4 WBML. NO EBML
17	4	E	18.73	28	1	1	1	0	01/03/06		DT867	1	400764	1	LOST PWR 07-23-05. HIGHWAY UNDER CONSTRUCTION
18	4	E	18.73	28		1		0	01/03/06		DT867	1	400764	2	LOST PWR 07-23-05. HIGHWAY UNDER CONSTRUCTION
19	4	E	18.73	28		1		0	01/03/06		DT867	1	400764	3	LOST PWR 07-23-05. HIGHWAY UNDER CONSTRUCTION
20	4	E	18.96	28	1	1	1	0	01/03/07		DT878	2	400270	1	LOST PWR 08-04-05. HIGHWAY UNDER CONSTRUCTION
21	4	E	18.96	28		1		0	01/03/07		DT878	2	400270	2	LOST PWR 08-04-05. HIGHWAY UNDER CONSTRUCTION
22	4	E	18.96	28		1		0	01/03/07		DT878	2	400270	3	LOST PWR 08-04-05. HIGHWAY UNDER CONSTRUCTION
23	4	E	19.39	28	1	1	1	0	01/04/06		DT425	1	401549	1	HIGHWAY UNDER CONSTRUCTION. CABINET REMOVED.
24	4	E	19.39	28		1		0	01/04/06		DT425	1	401549	2	HIGHWAY UNDER CONSTRUCTION. CABINET REMOVED.
25	4	E	19.39	28		1		0	01/04/06		DT425	1	401549	3	HIGHWAY UNDER CONSTRUCTION. CABINET REMOVED.
26	4	W	19.39	28		1		0	01/04/06		DT425	1	401510	1	HIGHWAY UNDER CONSTRUCTION. CABINET REMOVED.
27	4	W	19.39	28		1		0	01/04/06		DT425	1	401510	2	HIGHWAY UNDER CONSTRUCTION. CABINET REMOVED.
28	4	W	19.39	28		1		0	01/04/06		DT425	1	401510	3	HIGHWAY UNDER CONSTRUCTION. CABINET REMOVED.

Figure 44: Typical DFP spreadsheet information for District 4 (a)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	**VDS**	**Lane**	**Fwy**	**Dir.**	**P.M.**	**Cross Street**	**Dispatched by**	**MSID**	**Status**	**Problem**	**Related Cause**	**Solutions**	**Date**	**Tech**	**Comments**	**Referred/Deferred**	**tatus after vis**
2	400096	1	237	W	6.18	Great America Prkwy : rm-e-diag	David Armistad	E37EZ			Failed loops	Disabled cards	4/10/06	CV		Referred	Not fixed
3	400096	1	237	W	6.18	Great America Prkwy : rm-e-diag	David Armistad	E37EZ			Failed loops	Disabled cards	4/10/06	CV		Referred	Not fixed
4	400873	1	237	E	8.17	Zanker Road : rm-e-diag	David Armistad	E37EG			Card stayed on	Reset & adjust card	4/10/06	CV		None	Fixed
5	401186	1	280	N	5.45	On 280, 400' S of 289/17/880 IC	David Armistad	MVDS44			MVDS failed	Reset MVDS	4/10/06	CV		None	Fixed
6	401402	1	92	E	13.1	West of Vintage Park Dr. OC	David Armistad	DT036			Card stayed on	Reset & adjust card	4/10/06	CV		None	Fixed
7	401453	1	92	E	8.7	De Anza Blvd	David Armistad	DT083			EBML doesn' t existed		4/10/06	CV		Referred	Not fixed
8	400044	1	680	N	5.06	PARISH RD	Dist (4)	DT773			STATUS 7	COMM DOWN	4/13/06	HB/DT	RESET TOTAL CAB		
9	400050	1	238	N	15.41	KENT		DT144			Communication	No Comm to PeMS	4/13/06	DA	Reset 170E and modem, update firmware, ok	Referred	
10	400110	1	680	N	18.14	MONUMENT BL	Dist (4)	DT356			STATUS 7	COMM DOWN	4/13/06	HB/DT	RESET TOTAL CAB		
11	400115	1	238	S	15.41	KENT		DT144			Communication	No Comm to PeMS	4/13/06	DA	Reset 170E and modem, update firmware, ok	Referred	
12	400222	3	85	N	3.84	Saratoga Avenue	David Armistad	E37DR			Card stayed on	Reset & adjust card	4/13/06	CV		None	Fixed
13	400248	1	880	S	8.87	THORNTON		E33GY			Communication	No Comm to PeMS	4/13/06	DA	Reset modem, update firmware, ok	Referred	
14	400258	1	87	N	4.36	Lelong Avenue	David Armistad	E37ED			Under construction - lanes have been	N/A	4/13/06	CV		Referred	N/A
15	400325	1	101	N	31.82	Capitol Expressway	David Armistad	E37K8			Card stayed on	Reset & adjust card	4/13/06	CV		None	Fixed
16	400444	1	85	N	3.84	Blossom Hill Road	David Armistad	E37DK			Card stayed on	Reset & adjust card	4/13/06	CV		None	Fixed
17	400778	1	880	S	6.29	STEVENSON		E33GX			Communication	No Comm to PeMS	4/13/06	DA	Reset modem, update firmware, ok	Referred	
18	400792	2	85	S	10.47	Bascom Avenue	David Armistad	E37EM			Card stayed on	Reset & adjust card	4/13/06	CV		None	Fixed
19	400801	1	680	N	14.67	WB SR-24	Dist (4)	DT554			STATUS 7	COMM DOWN	4/13/06	HB/DT	UPGRADED MODEM		
20	401154	1	87	S	0.78	NB SR-85	David Armistad	DT126			There is no SBML	N/A	4/13/06	CV		None	N/A
21	401545	1	880	S	9.9	DECOTO		DT380			Communication	No Comm to PeMS	4/13/06	DA	Lanes ok to 170, RSSI very high	Referred	
22	401557	1	880	N	9.9	DECOTO		DT380			Communication	No Comm to PeMS	4/13/06	DA	Lanes ok to 170, RSSI very high	Referred	
23	401710	1	880	N	29.1	23RD		E33FE			Communication	No Comm to PeMS	4/13/06	DA	ually load template, modem dropped reg, no co	Referred	
24	400014	1	101	N	27.22	Bernal Road rm-n-diag	David Armistad	E37CT			Card stayed on	Reset & adjust card	4/17/06	CV		None	Fixed
25	400180	1	880	N	19.04	Hesperian	PeMS	DT397			Communications	modem not communicating	4/17/06	DA	Secured C2 harness, test ok at cabinet		
26	400181	1	101	N	27.02	Bernal Road rm-n-loop	David Armistad	E37CR			Card stayed on	Reset & adjust card	4/17/06	CV		None	Fixed
27	400312	1	880	S	19.37	Hesperian	PeMS	DT398			Deteriorating Equip	cards not functioning properly	4/17/06	DA	Adjusted frequency, test ok at cabinet		
28	400313	1	80	E	7.58	APPIAN WAY	Dist (4)	DT873			1	N/A	4/17/06	HB/DT	RESET CONTROLLER		
29	400666	1	880	S	19.04	Hesperian	PeMS	DT397			Communications	modem not communicating	4/17/06	DA	Secured C2 harness, test ok at cabinet		
30	400760	1	101	N	40.1	Guadalupe Parkway/Rte 87	David Armistad	DTB04			Card stayed on	Reset & adjust card	4/17/06	CV	DTB04 doesn't exist anymore	None	Fixed
31	401058	1	80	E	9.7	N/A	Dist (4)	DT071			1	N/A	4/17/06	HB/DT	RESET CONTROLLER		
32	401178	1	101	N	39.3	NB Rte 101 at North First St	David Armistad	MVDS36			MVDS Failed	Reset MVDS	4/17/06	CV		None	Fixed
33	401240	1	880	N	14.25	Industrial Pkwy	PeMS	DT387			Communications	modem not communicating	4/17/06	DA	et modem, cleared errors on 170E, test ok at cabinet		
34	401274	1	80	W	10.9	WILLOW P. OFF	Dist (4)	DT021			3	N/A	4/17/06	HB/DT	RESET CONTROLLER		
35	401481	1	580	E	44.8	Webster St.	PeMS	DT338			Deteriorating Equip	Open Loops	4/17/06	DA	ll EB loops read open at cabinet turned off card	Referred	
36	401503	5	80	W	2.41	Maritime/Grand	PeMS	DT650			Deteriorating Equip	Bad card	4/17/06	DA	Replaced bad card, test ok at cabinet		
37	401548	1	580	E	44.07	Chetwood	PeMS	DT336			Deteriorating Equip	Open Loops	4/17/06	DA	ll EB loops read open at cabinet turned off card	Referred	
38	401561	1	880	S	14.25	Industrial Pkwy	PeMS	DT387			Communications	modem not communicating	4/17/06	DA	et modem, cleared errors on 170E, test ok at cabinet		
39	401592	2	101	N	11.1	South of Church Ave. OC	David Armistad	DT472			Card stayed on	Reset & adjust card	4/17/06	CV		None	Fixed
40	401644	1	80	W	13.48	SAN PABLO	Dist (4)	DT971			6	N/A	4/17/06	HB/DT	LANE 1 IS AN EMERGENCY LANE	REFERRED	
41	401675	1	80	E	12.66	CUMMINGS SKYWAY	Dist (4)	DT972			2	N/A	4/17/06	HB/DT	NO PROBLEM FOUND		
42	401676	3	80	W	13.48	SAN PABLO	Dist (4)	DT971			3	N/A	4/17/06	HB/DT	NO PROBLEM FOUND		
43	401548	1	580	E	44.07	Chetwood	Charles	DT336			Open Loops	Install Loop	4/17/06	DA	ll EB loops read open at cabinet turned off card	Referred	
44	401503	5	80	W	2.41	Maritime/Grand	Charles	DT650			Deteriorating Equip	Bad card	4/17/06	DA	Replaced bad card, test ok at cabinet		
45	401561	1	880	S	14.25	Industrial Pkwy	Charles	DT387			Communications	modem not communicating	4/17/06	DA	et modem, cleared errors on 170E, test ok at cabinet		
46	401240	1	880	N	14.25	Industrial Pkwy	Charles	DT387			Communications	modem not communicating	4/17/06	DA	et modem, cleared errors on 170E, test ok at cabinet		
47	400180	1	880	N	19.04	Hesperian	Charles	DT397			Communications	modem not communicating	4/17/06	DA	Secured C2 harness, test ok at cabinet		
48	400666	1	880	S	19.04	Hesperian	Charles	DT397			Communications	modem not communicating	4/17/06	DA	Secured C2 harness, test ok at cabinet		
49	400529	5	880	N	19.37	Hesperian	Charles	DT398			Deteriorating Equip	cards not functioning properly	4/17/06	DA	Adjusted frequency, test ok at cabinet		
50	400312	1	880	S	19.37	Hesperian	Charles	DT398			Deteriorating Equip	cards not functioning properly	4/17/06	DA	Adjusted frequency, test ok at cabinet		
51	401481	1	580	E	44.8	Webster St.	Charles	DT338			Deteriorating Equip	Open Loops	4/17/06	DA	ll EB loops read open at cabinet turned off card	R	
52	401592	2	101	N	11.1	South of Church Ave. OC	David Armistad	DT472			Card stayed on	Reset & adjust card	4/17/06	CV		None	fixed
53	400181	1	101	N	27.02	Bernal Road rm-n-loop	David Armistad	E37CR			Card stayed on	Reset & adjust card	4/17/06	CV		None	fixed
54	400014	1	101	N	27.22	Bernal Road rm-n-diag	David Armistad	E37CT			Card stayed on	Reset & adjust card	4/17/06	CV		None	fixed
55	401178	1	101	N	39.3	NB Rte 101 at North First St	David Armistad	MVDS36			MVDS Failed	Reset MVDS	4/17/06	CV		None	fixed
56	400760	1	101	N	40.1	Guadalupe Parkway/Rte 87	David Armistad	DTB04			Card stayed on	Reset & adjust card	4/17/06	CV	sn't exist anymore , reconstruction of diagonal (	None	fixed
57	401676	3	80	W	13.48	SAN PABLO	David Armistad	DT971			3	N/A	4/17/06	HB	NO PROBLEM FOUND		
58	401644	1	80	W	13.48	SAN PABLO	David Armistad	DT971			6	N/A	4/17/06	HB	LANE 1 IS AN EMERGENCY LANE	REFERRED	
59	401675	1	80	E	12.66	CUMMINGS SKYWAY	David Armistad	DT972			2	N/A	4/17/06	HB	NO PROBLEM FOUND		
60	401274	1	80	W	10.9	WILLOW P. OFF	David Armistad	DT021			3	N/A	4/17/06	HB	RESET CONTROLLER		
61	401058	1	80	E	9.7	N/A	David Armistad	DT071			1	N/A	4/17/06	HB	RESET CONTROLLER		
62	400313	1	80	E	7.58	APPIAN WAY	David Armistad	DT873			1	N/A	4/17/06	HB	RESET CONTROLLER		

Figure 45: Typical DFP spreadsheet information for District 4 (b)

	VDS	Lane	Route	Direction	Post Mile	Pems Nov4 Status	Problem Type	Related Cause	Solution
2	715915	1	5	N	5.5	3	Deteriorating Equipment	Failed Loop	Install Loop
3	715915	2	5	N	5.5	3	Deteriorating Equipment	Failed Loop	Install Loop
4	715915	3	5	N	5.5	4	Deteriorating Equipment	Failed Loop	Install Loop
5	715916	1	5	S	5.5	4	Deteriorating Equipment	Failed Detector System	Repair Detector System
6	715920	1	5	S	6.64	1	Communication	Damaged Copper Com Line	Install Copper Com Line
7	715920	2	5	S	6.64	1	Communication	Damaged Copper Com Line	Install Copper Com Line
8	715920	3	5	S	6.64	1	Communication	Damaged Copper Com Line	Install Copper Com Line
9	715920	4	5	S	6.64	1	Communication	Damaged Copper Com Line	Install Copper Com Line
10	715921	1	5	S	6.76	3	Deteriorating Equipment	Failed Detector System	Repair Detector System
11	715921	2	5	S	6.76	3	Deteriorating Equipment	Failed Detector System	Repair Detector System
12	715921	3	5	S	6.76	3	Deteriorating Equipment	Failed Detector System	Repair Detector System
13	715933	1	5	N	10.33	1	Incomplete Installation	Missing Communications Signal	Provide Signal
14	715933	2	5	N	10.33	1	Incomplete Installation	Missing Communications Signal	Provide Signal
15	715933	3	5	N	10.33	1	Incomplete Installation	Missing Communications Signal	Provide Signal
16	715933	4	5	N	10.33	1	Incomplete Installation	Missing Communications Signal	Provide Signal
17	715938	3	5	N	12.18	3	Deteriorating Equipment	Failed Loop	Install Loop
18	715947	4	5	S	13.67	3	Communication	Faulty Configuration-PeMS/TMC	TMC/ PeMS Fix Configuration
19	715996	1	5	S	37.3	1	Incomplete Installation	Missing Copper Com Line	Install 6 pair twisted cable.
20	715996	2	5	S	37.3	1	Incomplete Installation	Missing Copper Com Line	Install 6 pair twisted cable.
21	715996	3	5	S	37.3	1	Incomplete Installation	Missing Copper Com Line	Install 6 pair twisted cable.
22	715996	4	5	S	37.3	1	Incomplete Installation	Missing Copper Com Line	Install 6 pair twisted cable.
23	715996	5	5	S	37.3	1	Incomplete Installation	Missing Copper Com Line	Install 6 pair twisted cable.
24	715996	6	5	S	37.3	1	Incomplete Installation	Missing Copper Com Line	Install 6 pair twisted cable.
25	716007	4	5	N	R46.77	1	Deteriorating Equipment	Failed Loop or DLC	Install Loop or DLC
26	716007	5	5	N	R46.77	1	Deteriorating Equipment	Failed Loop or DLC	Install Loop or DLC
27	716010	1	5	S	R49.5	3	Deteriorating Equipment	Failed Detector System	Repair Detector System
28	716010	2	5	S	R49.5	3	Deteriorating Equipment	Failed Detector System	Repair Detector System
29	716010	3	5	S	R49.5	3	Deteriorating Equipment	Failed Loop or DLC	Install Loop or DLC
30	716010	4	5	S	R49.5	3	Deteriorating Equipment	Failed Loop or DLC	Install Loop or DLC
31	716016	1	5	S	R54.2	2	Deteriorating Equipment	Failed Detector System	Repair Detector System

Figure 46: Typical DFP spreadsheet information for District 7 (a)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	
221	716895	3	5	S	8.93	PARAMOUNT	SHAWN	43	5	INTERMITTENT	Low Frequency	Adjusted Frequency	7/6/06	SL		No
222	716895	4	5	S	8.93	PARAMOUNT	SHAWN	43	5	INTERMITTENT	Low Frequency	Adjusted Frequency	7/6/06	SL		No
223	764766	1	101	S	9.83	UNIVERSAL 2	SHAWN	1556	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
224	764766	2	101	S	9.83	UNIVERSAL 2	SHAWN	1556	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
225	764766	3	101	S	9.83	UNIVERSAL 2	SHAWN	1556	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
226	764766	4	101	S	9.83	UNIVERSAL 2	SHAWN	1556	4	HIGH OCC.	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
227	764766	5	101	S	9.83	UNIVERSAL 2	SHAWN	1556	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
228	717486	1	101	S	9.31	BARHAM	SHAWN	166	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
229	717486	2	101	S	9.31	BARHAM	SHAWN	166	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
230	717486	3	101	S	9.31	BARHAM	SHAWN	166	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
231	717486	4	101	S	9.31	BARHAM	SHAWN	166	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
232	717486	5	101	S	9.31	BARHAM	SHAWN	166	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
233	764949	2	101	N	9.21	BARHAM	SHAWN	166	5	INTERMITENT	HIGH FREQUENCY	ADJUSTED CARD	7/5/06	OR		No
234	717511	1	101	S	20.96	BURBANK	SHAWN	415	5	INTERMITENT	BAD CARD AND MISS CONNECTED WIRES	PLACED CARD AND CONNECTED WI	7/5/06	OR		No
235	717511	2	101	S	20.96	BURBANK	SHAWN	415	4	HIGH OCC.	BAD CARD AND MISS CONNECTED WIRES	PLACED CARD AND CONNECTED WI	7/5/06	OR		No
236	717511	3	101	S	20.96	BURBANK	SHAWN	415	5	INTERMITENT	BAD CARD AND MISS CONNECTED WIRES	PLACED CARD AND CONNECTED WI	7/5/06	OR		No
237	717511	4	101	S	20.96	BURBANK	SHAWN	415	4	HIGH OCC.	BAD CARD AND MISS CONNECTED WIRES	PLACED CARD AND CONNECTED WI	7/5/06	OR		No
238	717489	1	101	S	10.53	VENTURA	SHAWN	170	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
239	717489	2	101	S	10.53	VENTURA	SHAWN	170	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
240	717489	3	101	S	10.53	VENTURA	SHAWN	170	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
241	717489	4	101	S	10.53	VENTURA	SHAWN	170	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
242	717489	5	101	S	10.53	VENTURA	SHAWN	170	3	CARD OFF	OPEN LOOP	INSTALL LOOP	7/5/06	OR		Ref
243	766600	1	60	E	28.97	E/B 60 W/O 71	SHAWN	2655	3	Card off	Rusty connectors	Cleaned connectors	7/5/06	VC		No
244	766600	2	60	E	28.97	E/B 60 W/O 71	SHAWN	2655	3	Card off	Rusty connectors	Cleaned connectors	7/5/06	VC		No
245	766600	3	60	E	28.97	E/B 60 W/O 71	SHAWN	2655	3	Card off	Rusty connectors	Cleaned connectors	7/5/06	VC		No
246	766600	4	60	E	28.97	E/B 60 W/O 71	SHAWN	2655	3	Card off	Rusty connectors	Cleaned connectors	7/5/06	VC		No
247	766599	1	60	E	28.97	E/B 60 W/O 71	SHAWN	2655	3	Card off	Rusty connectors	Cleaned connectors	7/5/06	VC		No
248	766601	1	60	W	28.97	W/B 60 W/O 71	SHAWN	2655	3	Card off	Rusty connectors	Cleaned connectors	7/5/06	VC		No
249	766602	1	60	W	28.97	W/B 60 W/O 71	SHAWN	2655	3	Card off	Rusty connectors	Cleaned connectors	7/5/06	VC		No
250	766602	2	60	W	28.97	W/B 60 W/O 71	SHAWN	2655	3	Card off	Rusty connectors	Cleaned connectors	7/5/06	VC		No
251	766602	3	60	W	28.97	W/B 60 W/O 71	SHAWN	2655	3	Card off	Rusty connectors	Cleaned connectors	7/5/06	VC		No
252	766602	4	60	W	28.97	W/B 60 W/O 71	SHAWN	2655	3	Card off	Rusty connectors	Cleaned connectors	7/5/06	VC		No
253	766619	1	60	E	29.51	RTE71/GAREY AVE 2	SHAWN	1037	3	Card off	No power at card cage	Restored power	7/5/06	VC		No
254	766620	1	60	E	29.51	RTE71/GAREY AVE 2	SHAWN	1037	3	Card off	No power at card cage	Restored power	7/5/06	VC		No
255	766620	2	60	E	29.51	RTE71/GAREY AVE 2	SHAWN	1037	3	Card off	No power at card cage	Restored power	7/5/06	VC		No
256	766620	3	60	E	29.51	RTE71/GAREY AVE 2	SHAWN	1037	3	Card off	No power at card cage	Restored power	7/5/06	VC		No
257	766620	4	60	E	29.51	RTE71/GAREY AVE 2	SHAWN	1037	3	Card off	No power at card cage	Restored power	7/5/06	VC		No
258	766621	1	60	W	29.51	RTE71/GAREY AVE 2	SHAWN	1037	3	Card off	No power at card cage	Restored power	7/5/06	VC		No
259	766622	1	60	W	29.51	RTE71/GAREY AVE 2	SHAWN	1037	3	Card off	No power at card cage	Restored power	7/5/06	VC		No
260	766622	2	60	W	29.51	RTE71/GAREY AVE 2	SHAWN	1037	3	Card off	No power at card cage	Restored power	7/5/06	VC		No
261	766622	3	60	W	29.51	RTE71/GAREY AVE 2	SHAWN	1037	3	Card off	No power at card cage	Restored power	7/5/06	VC		No
262	766622	4	60	W	29.51	RTE71/GAREY AVE 2	SHAWN	1037	3	Card off	No power at card cage	Restored power	7/5/06	VC		No
263	766644	2	60	E	29.15	RTE71/GAREY AVE 1	SHAWN	1039	5	Intermittent	High Hz, bad card	Replaced 222 card	7/5/06	VC		No
264	766644	1	60	E	29.15	RTE71/GAREY AVE 1	SHAWN	1039	2	Card off	Bad card	Replaced 222 card	7/5/06	VC		No
265	765456	1	60	W	27.86	PHILLIPS RANCH	SHAWN	1041	5	Intermittent	Low Hz, cross talk	Adjusted card	7/5/06	VC		No
266	716989	1	5	S	33.23	ROSCOE	SHAWN	238	3	CARD OFF	Open Loop Or DLC	Install Loop Or DLC	7/5/06	SL	PB At Median	Ref
267	716989	2	5	S	33.23	ROSCOE	SHAWN	238	3	CARD OFF	Open Loop Or DLC	Install Loop Or DLC	7/5/06	SL	PB At Median	Ref
268	716989	3	5	S	33.23	ROSCOE	SHAWN	238	3	CARD OFF	Open Loop	Install Loop	7/5/06	SL	Loop Cable Is Hard Copper	Ref
269	718389	2	5	N	37.37	OSBORNE 1	SHAWN	484	5	INTERMITTENT	Low Frequency	Adjusted Frequency	7/5/06	SL		No
270	717004	2	5	S	37.47	OSBORNE 2	SHAWN	487	4	HIGH OCCUPANCY	Cross Talking	Adjusted Frequency	7/5/06	SL		No
271	717006	2	5	S	37.84	TERRA BELLA	SHAWN	488	5	INTERMITTENT	Low Frequency	Adjusted Frequency	7/5/06	SL		No
272	717678	1	210	W	R39.52	AZUSA 1	SHAWN	1290	5	INTERMITTENT	Low Sensitivity	Adjusted Sensitivity	6/30/06	SL		No
273	717678	2	210	W	R39.52	AZUSA 1	SHAWN	1290	5	INTERMITTENT	Low Sensitivity	Adjusted Sensitivity	6/30/06	SL		No
274	717688	4	210	W	R41.68	GRAND 2	SHAWN	1286	4	HIGH OCCUPANCY	High Frequency	Adjusted Frequency	6/30/06	SL		No
275	717663	1	210	W	R30.49	BALDWIN 1	SHAWN	1303	3	CARD OFF	Poor Connection	Fixed Poor Connection	6/30/06	SL		No
276	761356	1	210	W	R33.76	MYRTLE AV	SHAWN	1298	3	CARD OFF	Card Was Off	Turn Card On	6/30/06	SL		No
277	718020	6	10	W	20.05	HERBERT	SHAWN	2488	5	INTERMITTENT	Poor Connection	Fixed Poor Connection	6/30/06	SL		No
278	718020	5	10	W	20.05	HERBERT	SHAWN	2488	4	HIGH OCCUPANCY	Poor Connection	Fixed Poor Connection	6/30/06	SL		No
279	767585	2	2	E	2.45	MOUNTAIN ST	SHAWN	1463	5	Intermittent	Cross talk, High Hz	Adjusted card	6/30/06	VC		No
280	764101	2	170	S	15.26	MAGNOLIA	SHAWN	391	5	Intermittent	lose and rusty connection	Cleaned and firmly attached connections	6/30/06	VC		No
281	717490	4	101	S	11.17	VINELAND	SHAWN	171	3	Card Off	Bad loops	Replace bad loops	6/30/06	VC	MIL are being repaved	Ref
282	717490	5	101	S	11.17	VINELAND	SHAWN	171	3	Card Off	Bad loops	Replace bad loops	6/30/06	VC	MIL are being repaved	Ref
283	768066	1	101	S	11.53	MOORPARK	SHAWN	172	5	Intermittent	Bad card, low Hz	Replaced 222 card	6/30/06	VC		No
284	[illegible]	2	5	N	[illegible]	OSMOND	SHAWN	2609	5	INTERMITENT	DLC WAS NOT CONNECTED	CONNECTED DLC	6/29/06	OR		[illegible]

Figure 47: Typical DFP spreadsheet information for District 7 (b)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
470	717224	3	10	W	39.05	4	775	Loop unstable	Install loop		3/16/06	V/J	Loop was not detecting properly	Referred			Open Loop
471	716694	5	405	N	20.6	4	2055	Failed loop	Install loop		3/17/06	J/S		Referred			Open Loop
472	761492	1	405	N	22.7	5	355	Card stayed on	Adjusted frequency		3/17/06	J/S		OK			Card Off
473	761492	2	405	N	22.7	5	355	Card stayed on	Adjusted frequency		3/17/06	J/S		OK			Card Off
474	761492	3	405	N	22.7	4	355	Card stayed on	Adjusted frequency		3/17/06	J/S		OK			Card Off
475	761492	4	405	N	22.7	4	355	Card stayed on	Adjusted frequency		3/17/06	J/S		OK			Card Off
476	717794	1	405	N	30.13	5	201	OK	Adjusted frequency		3/17/06	J/S		OK			None
477	718314	2	405	S	35.8	5	2066	Card stayed on	Adjusted frequency		3/17/06	J/S		OK			Card Off
478	767258	1	405	S	38.09	5	513	OK	Adjusted frequency		3/17/06	J/S		OK			None
479	765273	2	405	S	41.48	5	395	Card stayed on	Adjusted frequency		3/17/06	J/S		OK			Card Off
480	718232	2	405	S	3.37	5	17	Card stayed on	Adjusted frequency		3/17/06	O		OK			Card Off
481	716632	4	405	N	3.82	5	2048	Card stayed on	Adjusted frequency		3/17/06	O		OK			Card Off
482	717713	4	405	N	4.81	5	21	Crosstalking	Replaced card		3/17/06	O		OK			Card Off
483	717750	1	405	N	16.66	3	50	Card stayed on	Adjusted frequency		3/17/06	O		OK			Card Off
484	717750	3	405	N	16.66	5	50	Card stayed on	Adjusted frequency		3/17/06	O		OK			Card Off
485	717750	4	405	N	16.66	5	50	Card stayed on	Adjusted frequency		3/17/06	O		OK			Card Off
486	717945	4	605	N	19.5	VALLEY 2	1423		Fixed by Oscar/Vincent on 3/21/06		3/21/06	O/V					Card Off
487	762645	4	605	N	19.5	VALLEY 2	1423		Fixed by Oscar/Vincent on 3/21/06		3/21/06	O/V					Card Off
488		4	5	N	24.3	LOS FELIZ EB1	40		Fixed by Oscar/Vincent on 3/22/06		3/22/06	O/V					Card Off
489	716152	4	10	E	35.9	5	2100	Old card worked intermittenly	Replaced card		4/6/06	V	Fixed				Card Off
490	716760	3	605	N	R2.28	Centralia	2138		Old card works intermittenly	ced 222 card fo	4/10/06	JD		No	Fix		Card Off
491	716760	4	605	N	R2.29	Centralia	2138		Old card works intermittenly	ced 222 card fo	4/10/06	JD		No	Fix		Card Off
492	716775	1	605	S	R4.31	183RD	2139		Failed loop	Install loop	4/17/06	J		Referred	Not fixed		Open Loop
493	716776	1	605	S	4.9	3	2373	Card off	Open Loop	Install Loop	4/19/06	OR/SM	No loop at pull box	Referred			Open Loop
494	716776	1	605	S	4.9	3	2373	Card off	Open Loop	Install Loop	4/19/06	OR/SM	No loop at pull box	Referred			Open Loop
495	716776	2	605	S	4.9	3	2373	Card off	Open Loop	Install Loop	4/19/06	OR/SM	No loop at pull box	Referred			Open Loop
496	716776	3	605	S	4.9	3	2373	Card off	Open Loop	Install Loop	4/19/06	OR/SM	No loop at pull box	Referred			Open Loop
497	716776	4	605	S	4.9	3	2373	Card off	Open Loop	Install Loop	4/19/06	OR/SM	No loop at pull box	Referred			Open Loop
498	716778	1	605	S	R5.43	N OF 91	2440		Failed Loop	Install Loop	4/12/06	JD	There is no loops at pull box	No	not fixed		Open Loop
499	716778	2	605	S	R5.43	N OF 91	2440		Failed Loop	Install Loop	4/12/06	JD	There is no loops at pull box	No	not fixed		Open Loop
500	716778	3	605	S	R5.43	N OF 91	2440		Failed Loop	Install Loop	4/12/06	JD	There is no loops at pull box	No	not fixed		Open Loop
501	716778	4	605	S	R5.43	N OF 91	2440		Failed Loop	Install Loop	4/12/06	JD	There is no loops at pull box	No	not fixed		Open Loop
502	716778	5	605	S	R5.43	N OF 91	2440		Failed Loop	Install Loop	4/12/06	JD	There is no loops at pull box	No	not fixed		Open Loop
503	716778	6	605	S	R5.43	N OF 91	2440		Failed Loop	Install Loop	4/12/06	JD	There is no loops at pull box	No	not fixed		Open Loop
504	716778	1	605	S	R5.43	3	2440	Card off	Open loop	Install loop	4/17/06	JD		Referred			Open Loop
505	716784	5	605	N	R6.29	5	2140	Old card worked intermittently	Replaced card		4/10/06	J	Fixed				Open Loop
506	716800	3	605	N	R10.91	Placita	2144		Failed Loop	Install Loop	4/10/06	JD			not fixed		Open Loop
507	716819	2	605	N	R14.89	3	2146	Card off	Open loop or DLC	stall loop or DL	4/17/06	JD	t have access to pull box (constr	Referred			Bad Equipment
508	716829	2	605	S	R17.1	S OF 60	2449		Old card works intermittenly	Light on & off	4/12/06	JD	l box, loops and cables were dam	No	not fixed		Card Off
509	716829	1	605	N	17.1	3	2449	Card off	Damaged spliced	Re-spliced	4/20/06	OR/SM	iously visited on 4/19/2006 by OR	Fixed			Card Off
510	716829	2	605	N	17.1	3	2449	Card off	Damaged spliced	Re-spliced	4/20/06	OR/SM	iously visited on 4/19/2006 by OR	Fixed			Card Off
511	716829	3	605	N	17.1	3	2449	Card off	Damaged spliced	Re-spliced	4/20/06	OR/SM	iously visited on 4/19/2006 by OR	Fixed			Card Off
512	716841	1	605	S	23.952	Arrow 1	1428		Failed Loop or DLC	stall Loop or D	4/10/06	JD	Pull box at center divider	No	not fixed		Bad Equipment
513	716841	2	605	S	23.952	Arrow 1	1428		Failed Loop or DLC	stall Loop or D	4/10/06	JD	Pull box at center divider	No	not fixed		Bad Equipment
514	716841	3	605	N	23.952	Arrow 1	1428		Failed Loop	Install Loop	4/10/06	JD	There is no loops at pull box	No	not fixed		Open Loop
515	716841	4	605	N	23.952	Arrow 1	1428		Failed Loop	Install Loop	4/10/06	JD	There is no loops at pull box	No	not fixed		Open Loop
516	716857	1	710	N	16.5	3	2210	Card off	Bad card and it was turned off	Replaced card	4/21/06	OR/SM		4 (High occ.)			Card Off
517	716942	4	5	N	18.71	4	34	Card stayed on	Replaced card		4/6/06	J	4 (High Occ)				Card Off
518	716946	1	5	S	20.33	5	146	Old card worked intermittenly	Adjusted frequency & sensitivity		4/6/06	J	Fixed				Card Off
519	716946	1	5	S	20.33	5	146	Intermittent	Card stayed on	Reset card	4/18/06	JD		5 (Intermittent)			Card Off
520	716958	5	5	S	23.58	5	96	Old card worked intermittenly	Adjusted frequency & sensitivity		4/6/06	J	Fixed				Card Off
521	716958	1	5	S	32.28	3	239	Card off	Open loop or DLC	stall loop or DL	4/20/06	JD		Referred			Bad Equipment
522	716958	5	5	S	23.58	3	96	Card off	Controller was not counting	the controller	4/20/06	JD		Fixed			Bad Software
523	717002	1	5	S	36.75	3	232	Card off	Open loop	Install loop	4/20/06	JD		Referred			Open Loop
524	717002	2	5	S	36.75	3	232	Card off	Open loop	Install loop	4/20/06	JD		Referred			Open Loop
525	717002	3	5	S	36.75	3	232	Card off	Open loop	Install loop	4/20/06	JD		Referred			Open Loop
526	717002	4	5	S	36.75	3	232	Card off	Open loop	Install loop	4/20/06	JD		Referred			Open Loop

Figure 48: Typical DFP spreadsheet information for District 7 (c)