The quality of loop data and the health of California's freeway loop detectors

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Summary

The report evaluates the quality of loop data and the health of loop detectors in California freeways in Districts 3, 4, 7, 8, 11, and 12. The findings are based on (1) a comparison of loop data with data obtained from tach vehicle runs and from census counts and (2) an intensive analysis of loop detector data from these districts for one month.¹

1. Loop detector data are at least as accurate as those obtained from more expensive alternatives of tach vehicle runs and census counts. Loop data are much more valuable since they provide continuous and statewide coverage.

2. For each district, we calculate the following numbers:
   a) Percentage of missing samples—the fraction of samples that should have been received from field equipment but were not. The vast majority of missing samples are due to loops that reported no samples for the entire month. Missing samples are caused by various factors, analyzed in this report.
   b) Percentage of bad samples—the fraction of samples that were received but which statistical tests classify as unreliable. Bad samples indicate detector loop malfunction. With the exception of District 4, only a small fraction of received samples are bad.
   c) Percentage of good samples—the percentage of samples that should have been received and were good. This is the most important indicator of health. A healthy system should indicate percentages above 90. By this standard, California has no healthy district. The percentage of good samples varies: D3—72%, D4—24%, D7—62%, D8—41%, D11—78%, D12—51%.

Missing samples account for the vast majority of lack of good data.

3. We compare loop detector status in two D7 freeways, 405 and 210, during October 2001 and February 2002. In between these two periods, contractors apparently fixed malfunctions. However, the data reveal no significant improvement in detector health. This suggests that the work done was ineffective.

3. Some loops are misidentified in the D7 ATMS database: a loop that the database records as being, say, in lane 1 is in fact located in another lane. The misidentification was discovered by accident and, in the absence of any systematic analysis, we can’t say how extensive is this misidentification.

4. There are sound statistical methods for “fixing” bad or missing samples, that is, replacing those samples by values based on spatial and temporal correlation with values of reliable samples. These methods will be addressed in a future report.

¹ Only 5 days worth of data from D11, San Diego, were analyzed.

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Caltrans Traffic Operations and Planning need reliable data for their work to be effective. Reports like this one can be generated on a regular (daily, weekly, monthly) basis to pinpoint malfunctioning detector locations, and precisely monitor the performance of contractors responsible for correcting malfunctions. An improved process of work may be obtained if contracts can be based on outcomes. A further refinement of these reports can be used to schedule work on the basis of which freeway sections need the most immediate attention.

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1. Introduction

The loop detector system—comprising the detectors themselves and the communication links over which detector data are transferred to district TMCs—generates data about conditions on California’s freeways. The table below gives the number of loops by district:

<table>
<thead>
<tr>
<th>District ID</th>
<th>Name</th>
<th>Mainline loops</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Sacramento</td>
<td>334</td>
</tr>
<tr>
<td>4</td>
<td>Bay Area</td>
<td>4679</td>
</tr>
<tr>
<td>7</td>
<td>Los Angeles</td>
<td>5340</td>
</tr>
<tr>
<td>8</td>
<td>San Bernardino</td>
<td>500</td>
</tr>
<tr>
<td>11</td>
<td>San Diego</td>
<td>837</td>
</tr>
<tr>
<td>12</td>
<td>Orange County</td>
<td>2910</td>
</tr>
</tbody>
</table>

Table 1 Number of mainline loops by district.

The loops generate samples every 30 seconds. These samples are sent to the district ATMS and to the PeMS system. For the entire state, the system generates nearly two gigabytes (two billion bytes) of data each day. The district ATMS systems use these data for real time traffic operations. PeMS archives these data and provides many applications for use in intelligent traffic operations, planning, and investment decisions.

The loop detector system is the only source of real time and historical data about freeway performance. Any effort to improve freeway management will rely heavily on these data. However, the detector system health maintenance receives negligible Caltrans attention.

Successive sections of this report analyze the loop detector system along four dimensions: accuracy, health, maintenance, and completeness. It concludes with a suggestion to institute an effective loop health maintenance system.

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2 Communication links in California freeways are mostly over multidrop telephone lines. D4 uses a significant number of wireless links. RTMS and CCTV are alternative detector technologies, but they are not widely deployed and have their own limitations. At least five years away are technologies based on cellular phones, tag readers, etc.

3 This study covers mainline loops alone, excluding HoV lanes and loops on ramps. Generally, data from loops on ramps are of worse quality than mainline loops.

4 There are two kinds of loops: ‘single’ loop detectors report count and occupancy; ‘double’ loops report speed as well. With the exception of D4, most loops are single loops. PeMS takes single loop data and estimates speed.

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2. Accuracy of loop data

There is a perception that loop data are inaccurate. Caltrans has expensive programs to collect statistics that could also be obtained from loop data. We compare estimates from two such programs—tach vehicle runs and census counts—with PeMS’ estimates. As shown below, PeMS estimates are as accurate as these alternative programs.

It follows that performance measures and other inferences based on PeMS are far superior to tach vehicle runs and census counts. The latter provide data very infrequently and in a very few locations. Loop data are collected continuously and cover all freeway sections where loop detectors are present. As a result performance measures obtained by PeMS such as vehicle counts, congestion, level of service, and travel times, which are intrinsically statistical, are much more reliable and comprehensive than the alternative methods used by Caltrans.

2.1 Tach vehicle runs

Figure 1 compares the speeds estimates by tach vehicle runs at six different locations on I-10E on 10 August 2000 with speed estimates routinely calculated by PeMS throughout the state on a 24-hour basis.\(^5\) The following reservations should be kept in mind in evaluating the comparisons:

- a. The tach vehicle speed estimates are based on runs by vehicles paced roughly 15 minutes apart. By contrast, PeMS estimates are updated every 5 minutes. As a result, tach vehicle estimates miss speed variations that occur within successive 15 minutes but are visible in the PeMS estimates.
- b. The locations of the tach vehicle estimates are not identical to the locations of loop detectors, so the estimates cannot match perfectly. This is especially the case during periods of congestion when speed differences in nearby locations can be large, as is the case in three of the runs.
- c. PeMS makes lane-by-lane estimates. We don’t know the lane in which the tach vehicle traveled, so the PeMS estimate used is the average speed across all lanes.
- d. It appears from the plots that the tach vehicle estimates in two cases are erroneous, since they record a speed of 25 mph while 15 minutes earlier and 15 minutes later they record a speed of 60 mph at the same location! The loop detector data show no such wild fluctuation.

These reservations, however, do not diminish the overwhelming impression of the visual comparison: PeMS speed estimates are at least as accurate as those of tach vehicle runs.

2.2 Census counts

We compare hourly vehicle census counts at six locations in District 12 for the entire month of December 2001 with counts made by PeMS at nearby locations. The census locations were carefully selected to be close (within 0.3 miles) of mainline loops in the PeMS database. More importantly, there is no on- or off-ramp between the census locations and the mainline loops.\(^6\)

\(^5\) We are grateful to Tom Choe of District 7 for giving us the tach vehicle data.

\(^6\) We are grateful to Joe Avis for selecting census locations that match the mainline loops and for giving us the census data. Census counts are obtained from well-maintained loops. This one month-long data set is as close to “ground truth” that is possible to get at a reasonable cost.

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Table 2 gives a summary comparison. Since the loop detector system provided no samples from route 605, we are unable to compare census data at two of the six locations. At one location on Route 55-S, the detector in lane 1 reported no samples.

<table>
<thead>
<tr>
<th>Census Number</th>
<th>Route</th>
<th>Direction</th>
<th>Postmile</th>
<th>Primary dir’n VDS (North)</th>
<th>Comment</th>
<th>Mean % error of daily counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>12901</td>
<td>5</td>
<td>North</td>
<td>5.25</td>
<td>1204306</td>
<td></td>
<td>1.29</td>
</tr>
<tr>
<td>12901</td>
<td>5</td>
<td>South</td>
<td>5.25</td>
<td>1204301</td>
<td></td>
<td>1.32</td>
</tr>
<tr>
<td>12909</td>
<td>55</td>
<td>North</td>
<td>2.70</td>
<td>1203021</td>
<td></td>
<td>1.36</td>
</tr>
<tr>
<td>12209</td>
<td>55</td>
<td>South</td>
<td>2.70</td>
<td>1203016</td>
<td>Lane1 samples are missing</td>
<td>29.5</td>
</tr>
<tr>
<td>12219</td>
<td>605</td>
<td>North</td>
<td>0.70</td>
<td>1202501</td>
<td>No samples</td>
<td>N/A</td>
</tr>
<tr>
<td>12219</td>
<td>605</td>
<td>South</td>
<td>0.70</td>
<td>1202507</td>
<td>No samples</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Table 2 Comparison of vehicle census counts and PeMS counts**

The first three rows in Table 2 show that a PeMS estimate of daily vehicle counts differs from a census count by less than 1.4%. The numbers in the last column are calculated by the formula

\[
\frac{1}{31} \sum_{t=1}^{31} \left| \frac{\text{PeMS vehicle count on day } t - \text{Census vehicle count on day } t}{\text{Census vehicle count on day } t} \right|.
\]

Figure 2 compares daily census and PeMS counts for the entire month at the first four locations listed in Table 2. The plot on the bottom right is for the location with no samples from lane 1.

Figure 3 compares hourly census counts with PeMS 5-minute counts (multiplied by 12) for four randomly chosen days at the first location listed in Table 2. (Note that the 5-minute PeMS plots provide information about variation in counts within the hour that is missed by hourly census counts.)

The conclusion is inescapable that data form functioning loop detectors are as accurate as census counts. Moreover, PeMS estimates are available on a 24-hour basis, throughout the state.

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3. Health of loop detectors

Each loop detector is polled every 30 seconds, so a loop detector should receive 2880 samples per loop per 24-hour day. Malfunctions reduce this number, resulting in missing samples. So one indicator of health is the fraction of missing samples.

A received sample may be ‘bad’—statistical tests declare that it is unreliable. Typically, bad samples report constant values (e.g. all zeros) or values that are unreasonably high or low. Bad samples are caused by detector (as opposed to communication) malfunction.

Good samples are samples that are neither missing nor bad. A healthy detection system should have at least 90 percent good samples. By this standard, California’s system is in poor health. The health varies greatly by district. Table 3 summarizes the key health indicators. The numbers refer to data from all loop detectors in Districts 3, 4, 7, 8, 11, 12 for the month of October 2001.\footnote{For District 4, data are for December 2001, since the communication system was being changed in October 2001. For District 11, the data cover five days.}

<table>
<thead>
<tr>
<th>District ID and Name</th>
<th>Number of detectors</th>
<th>% good samples</th>
<th>% bad samples</th>
<th>% missing samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, Sacramento</td>
<td>334</td>
<td>72</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>4, Bay Area</td>
<td>4679</td>
<td>24</td>
<td>37</td>
<td>39</td>
</tr>
<tr>
<td>7, Los Angeles</td>
<td>5340</td>
<td>62</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>8, San Bernardino</td>
<td>500</td>
<td>41</td>
<td>11</td>
<td>48</td>
</tr>
<tr>
<td>11, San Diego</td>
<td>837</td>
<td>78</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
<td>12, Orange Co</td>
<td>2910</td>
<td>51</td>
<td>7</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 3 Key health indicators by district.

A major cause of poor health is missing samples, due to various reasons: mislabeled, parallel, or open loops; missing, loose, or switched-off cards; controller malfunctions; and interrupted communications. The detector fitness program (DFP) crews inspect controllers, conduct a variety of diagnostic tests, and fix or recommend fixing malfunctions. The PeMS group and the DFP contractor are currently engaged in a joint effort to use PeMS as a tool to make the work of the DFP crew more effective.

We further analyze missing samples to understand spatial variation—do a few detectors account for most missing samples, or do many detectors contribute—and temporal variation—do a few days account for most missing samples, or do missing samples occur over many days.

Figures 4 and 5 provide some details. The plots in the left column for each district are obtained as follows. For each district we arrange the loops from worst to best according to the fraction of missing samples they reported for the month.

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In District 3, 50 out of 334 loops report no samples for the entire month; the next best 150 detectors missed between 10 and 20 percent of the samples; the remaining missed fewer than 10 percent of the samples. The ratio of the gray area to the area of the rectangle is equal to the fraction of the missing samples. Since the worst 50 loops (those reporting no samples at all) accounts for more than 60 percent of the gray area, if these loops were functioning, the number of missing samples would decrease by 60 percent, i.e., we would have only 6 percent missing samples. Correspondingly the percentage of good samples would increase from 72 percent to 82 percent.

In District 4, 1000 out of 4679 loops reported no samples for the entire month, accounting for 60 percent of the missing samples. If these loops were functioning, the number of missing samples would decrease to about 16 percent, while the percentage of good samples would increase from 24 to 48 percent.

In District 7, 700 out of 5340 loops reported no samples for the entire month, accounting for about 50 percent of the missing samples. If these loops were functioning, the number of missing samples would decrease to about 12 percent, and the number of good samples would increase from 61 to 73 percent.

In District 8, 230 out of 500 loops reported no sample for the entire month, accounting for about 80 percent of the missing samples. If these detectors were functioning, the number of missing samples would decrease by 80 percent to about 10 percent, and the number of good samples would increase from 41 to about 79 percent.

In District 12, 1300 out of 2910 loops report no samples for the entire month, accounting for about 90 percent of the missing samples. If these detectors were functioning, the number of missing samples would decrease to about 4 percent, and the number of good samples would increase 51 to 89 percent.

We now turn to the distributions in the column on the right in Figures 4, 5. For each loop we classify each day as “bad” if the majority of the samples for that day were missing or were bad, and we classify that day as “good” if the majority of the samples were good. We then arrange the loops from worst to best according to the number of bad days.

In District 3, about 80 out of 334 loops had all bad days. In District 4, 3000 out of 4679 loops had all bad days. In District 7, 1500 out of 5340 loops had all bad days. In District 8, 280 out of 500 had all bad days. In District 12, 1300 out of 2910 loops had all bad days.

This analysis leads to the following conclusion:

In each district, one can classify loops as “good” or “bad”. The good loops account for most of the good samples, the bad loops account for most of the missing and bad samples. A relatively small portion of missing or bad samples comes from good loops; conversely, a very small portion of good samples comes from bad loops.

This conclusion is significant because it points directly the design of an effective loop health maintenance strategy suggested in Section 5.

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4. Current maintenance strategy

The Caltrans Detector Fitness Program (DFP) hires contractors to inspect loop detectors. A crew of two technicians visits detector controller cabinets sequentially, one freeway at a time. At each location, the crewmembers perform a set of diagnostic tests on the physical loop installation and the controller. They fill out a standardized inventory form with the results of the diagnostics, including electrical characteristics, such as resistance to ground, and qualitative comments, such as “card is mislabeled.” In District 7 (Los Angeles), DFP does not fix most malfunctions, even if it is as simple as replacing a faulty detector card. This is because some of the detectors are part of the ramp metering system, and Caltrans is worried that a change to a detector condition may have unknown effects on the ramp metering. Instead, the crewmembers fill out a maintenance ticket for each malfunction location. This ticket goes to the Caltrans maintenance group, who has the authority to fix loop detectors. However, this process takes a long time and there is no verification of whether a fix has actually been performed. In other districts, the agreement between the DFP contractor and the district may be different, and the contractor could be allowed to perform simple fixes. The DFP has a separate crew to inspect communications links.

DFP inspected and made reports on loops on the freeways including I-210 and I-405 in Los Angeles in October 2001. We performed a study to verify any changes in data quality before and after the DFP inspections. The results are not encouraging. While there were fewer bad loops on I-405 after DFP, the number of bad loops on I-210 actually increased. The district as a whole showed very little difference in overall loop quality before and after DFP.

<table>
<thead>
<tr>
<th>Freeway</th>
<th>Malfunction Type</th>
<th>Before</th>
<th>After</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>Loops with no data</td>
<td>3%</td>
<td>11%</td>
<td>+7%</td>
</tr>
<tr>
<td></td>
<td>All bad loops</td>
<td>20%</td>
<td>22%</td>
<td>+2%</td>
</tr>
<tr>
<td>405</td>
<td>Loops with no data</td>
<td>13%</td>
<td>16%</td>
<td>+3%</td>
</tr>
<tr>
<td></td>
<td>All bad loops</td>
<td>51%</td>
<td>32%</td>
<td>-19%</td>
</tr>
<tr>
<td>Entire District</td>
<td>Loops with no data</td>
<td>9%</td>
<td>11%</td>
<td>+2%</td>
</tr>
<tr>
<td></td>
<td>All bad loops</td>
<td>33%</td>
<td>29%</td>
<td>+4%</td>
</tr>
</tbody>
</table>

Table 4. District 7 data quality before and after DFP.

Based on this comparison, one must conclude that the DFP maintenance in District 7 was not effective. Part of this must be attributed to the fact that the DFP crew cannot fix most loop errors themselves, and must submit a ticket. There is no feedback on when, if ever, the reported errors are fixed. This points to a deficiency in the current maintenance strategy: there needs to be a feedback loop to complete the diagnose-repair process. PeMS could be used to verify the effectiveness of field repairs.

PeMS is also a powerful tool that can help the field technicians diagnose loop errors, increasing productivity and accuracy. A close examination of its field reports showed that DFP found some of the bad loops identified by PeMS, particularly those whose output is all zero. But PeMS was able to identify other bad loops that were not found to be bad by DFP. These include loops with communications failures and those that failed in subtler ways, such as intermittent failures. In the trip report from a visit to detector locations in LA, we showed that most of the loop malfunctions could be diagnosed online from PeMS. The maintenance technician can get a clear picture of which loops are good, which have no communication, which are bad, and what are the likely causes. We are currently working with DFP to customize such a diagnostics tool for the technicians.

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4. Misidentification of loops

The ATMS database identifies each loop by the ID of the vehicle detector station (VDSID) and the lane number in which the loop is located (lane 1 corresponds to the innermost or ‘fast’ lane). Loops must be correctly identified; otherwise inferences based on loop data will be seriously biased. By accident we found one loop that is misidentified, reported below. This example has prompted us to look a little further. That investigation suggests that misidentification is not infrequent. However, we have not launched a systematic study and so we won’t discuss this issue further.

The two PeMS plots in Figure 6 give lane-by-lane speeds on 5 lanes at VDS 717550 and 717551 on 405-S and 405-N respectively, for a 24-hour period beginning midnight on October 3, 2000. Observe that in the upper figure, between 6 and 9 am, lane 1 registers 20 mph while the other lanes register 60 mph. Between 5 and 6 pm, the situation is reversed: lane 1 indicates 60 mph, while the rest indicate much lower speeds.

In the lower figure, on 405-N, between 6 and 9 am, lane 3 is moving at 60 mph while the others are crawling at 15 mph. Between 5 and 6 pm, the situation is reversed.

This pattern persists for everyday one cares to look, so that something must be wrong. The mystery is solved if we exchange the identifications of the two contrarian loops. It is easy to conjecture what has happened: either the two VDSs are in the same cabinet and the loops are switched there, or there are incorrect entries in the ATMS table.
5. An effective loop maintenance strategy

The analysis above leads to two important conclusions:

1. The poor health of the detector system is due to communication or detector station malfunction, except in District 4, where loop malfunctions are also significant.
2. Reports like this one can accurately locate the sources of poor data and diagnose the kind of malfunction that is responsible. Moreover, the effectiveness of the work done to correct the malfunction can be immediately determined.

These conclusions point directly to a simple and cost-effective detector health maintenance strategy, which employs the following steps.

1. Set a 90 percent good sample target for each district.
2. For each district prepare a list of worst performing detectors, group them by freeway, and prioritize the freeways.
3. Set a target date for the maintenance of each freeway.
4. Issue maintenance contracts that are based on performance.
5. Monitor the performance.
6. Begin a process to measure health statistics (e.g. the mean time between failures) to determine the resources needed to maintain good health on a continuing basis, after the target level of 90 percent is achieved.
Figure 1. Comparison of speed estimates by tach vehicle runs and PeMS.

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Figure 2. Comparison of daily census (dotted line) and PeMS counts (solid line) for one month at four locations in Table 2.
Figure 3. 5-minute PeMS counts vs hourly census counts over four days at the first location in Table 2.
Figure 4. Details of missing samples in Districts 3, 4, 7.
Figure 5. Details of missing samples in Districts 8, 12.
Figure 6. Lane-by-lane speeds at two different VDS stations. Loops in lane 3 in VDS 717751 and in lane 1 in VDS 717750 have been switched.