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Pravin Varaiya, Roberto Horowitz**

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Deliver a Set of Tools for Resolving Bad Inductive Loops and Correcting Bad Data

Final Report of Project TO6327

California PATH

Project Team

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Key Words

inductive loop, faulty loop data, loop fault detection, data correction and imputing, portable loop fault diagnosis tool

Abstracts

This report documents a practical work conducted at California PATH for developing a portable tool to be used at the control cabinet level to accurately diagnose any fault(s) of a loop detection system (including loop circuits, loop cards, cable links, etc.), to check the detection accuracy, to deal with sensitivity of detector card, and to correct the faulty data. To achieve these functionalities at the low level, it is necessary to utilize an independent source as a baseline data to compare against the loop detection system output. Such a comparison also permits an evaluation of the loop system. Since multiple-vehicle tracking technologies using digital video camera on freeways have been well-developed and tested at PATH, it is used as the baseline measurement in the portable tool for the loop fault diagnosis. This report presents the development of a prototype system including the hardware, the software, the data communication method, and the algorithms. Some preliminary consideration has also been conducted on lower (control cabinet) level data correction and communication system reliability of several Caltrans District for sensor data passing. Future work will be on systematic loop fault detection and lower level data correct.

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Executive Summary

Inductive Loops are widely used in California for traffic detection and monitoring. However, several faults may appear here and there in a loop detector system including the loop circuit buried in the ground, cable, loop card, and the communication systems used for data passing from the traffic control cabinet to TMC. Any fault may cause faulty data received in TMC, which directly affects traffic management and control, and traveler information. To achieve high performance for highway operation and planning, it is very critical to have high quality data. Thus to maintain a healthy loop detector system is absolutely necessary. Since traffic monitoring system with loops is large scale, one needs to know in time which loop has what problem precisely in order to fix it. There should be a systematic and effective way to diagnose the fault(s). Traditional approach for loop fault diagnosis was through aggregated data analysis in two levels: (a) macroscopic level as in TMC (Transportation Management Center) or PeMS (Performance Measurement System) in California, which uses highly aggregated data to look at loop problems related to an area; (b) mesoscopic level, which involves synchronized data for a section of freeways involving several control cabinet such as Berkeley Highway Lab (BHL). Those indirect approaches can diagnose certain type of system faults to some extent. Due to the communication error such as packet loss, it was difficult to tell exactly where and what is the fault exactly. This study proposed a combined approach: to find out certain system faults in higher level through data analysis, where one can also identify suspicious loops; and to diagnose faults in the inductive loop system directly at the traffic control cabinet level. The proposed approach is to use two independent synchronized real-time data streams: (a) one is from video camera based vehicle tracking, which is mounted on a mobile extractable pole focused at the loops in the ground; and (b) the other is the loop inductance obtained by direct interface with the loop detector card in the control cabinet. Comparison of the two data provides a direct way for fault diagnosis. Communication system is indispensible for data passing for data collection and integration for traffic operation and planning purposes. However, data loss is very common as passing through communication systems. It is imperative to find out which communication system is more reliable and to make a recommendation to Caltrans with improvement strategies.

Inductive Loops are widely used in California for traffic detection and monitoring. Extensive studies have been conducted to improve loop detection system performance. This section reviews previous work on faulty loop data analysis for correction and faulty loop diagnosis to some level of details. It is necessary to distinguish faulty loop data analysis and loop fault detection according to the data level. According to the level of data used, it divides the work in three levels: (1) macroscopic level as in TMC (Transportation Management Center) or PeMS (Performance Measurement System) in California, which uses highly aggregated data to look at loop problems related wide range; (2) mesoscopic level, which involves synchronized data for a section of freeways involving several control cabinet such as Berkeley Highway Lab (BHL); and (3) microscopic level: or at a control cabinet level including all the loop stations involved. Corresponding data correction methods are also briefly reviewed.

It is our opinion that high quality of data is absolutely necessary for all level of application in Active Traffic Management and Planning. Such data would require high quality basic sensor data and reliable communication system. Data quality from sensors depends on two factors:

- sensor detection system working condition
    - normal mode
    - error mode
        - persistent error caused by sensor system fault
        - intermittent error caused by sensor measurement noise
        - external uncertainty such as vehicle relative location to the sensor
- sensor characteristics
    - sensor measurement noise/error compared to ground truth
    - physical mechanism and its limit
    - environmental condition effect

To have a accurate and reliable data detection system, it is imperative to develop and build the following functions in the system:

- automatically detect/isolate the detector fault and its location as quickly as possible
- automatically correct the error by some software approach if possible

- establish a systematic sensor detection system maintenance regulation and implementation mechanism
- field operation to detect and correct those error that could not be detected, isolated, or corrected only from data side and by software.

Besides, it is also noted that data processing method to estimate the relevant traffic parameters from the basic sensor data also affect the estimation error which traffic engineers should also pay attention to.

In this sense, data quality largely depends on the quality of lower level sensor data. If the basic sensor data reading has a high quality, and if the data processing for traffic state parameter estimation in all the application levels are appropriate, high quality application data can be generated. The sensor detection and data correction strategies developed in this project is for this purpose.

This portable tool is composed of (a) a tractable pole with maximum height over 50 ft on a mobile trailer; (b) a PTZ camera mounted on top; (c) a computer laptop for real-time image processing for multiple lane vehicle tracking; (d) a computer laptop interfacing with loop card inserted in Controller cabinet; (e) wireless communication between the two computers; (f) a whole set of software to compare the loop detection signal and the vehicle detection signal from video tracking for loop fault detection. This report presents the preliminary development of the system including the hardware, the software, the data communication method, and the algorithm. Some preliminary consideration has been conducted on lower (control cabinet) level data correction and communication system reliability of several Caltrans District for sensor data passing. Future work will be on systematic loop fault detection and lower level data correct.

Chapter 1. Introduction

A systematic approach to detecting faulty loops is crucial to traffic operation, traveler information, and Corridor Management. Traffic detection systems are widely used for traffic management and control in California. The statewide *sensor system* consists of over 25,000 sensors located on the mainline and ramps, and grouped into 8,000 vehicle detector stations (VDS). Over 90 percent of the sensors use inductive loops. However, loop data are not reliable. The loop data delivered to TMC may contain error created at a point or several points between the loop detector and the TMC database, which presents a great challenge to loop fault detection. To solve this problem, it is necessary to take a systematic approach. This approach is composed of three complementary tasks: (a) loop fault detection; (b) faulty loop data correction/imputation; and (c) loop detection system maintenance. In our previous work [16], we categorized the loop fault detection approaches into three levels: (i) Macroscopic Level: such as the TMC/PeMS; (ii) Mesoscopic Level - a stretch of freeway such as the Berkeley Highway Lab (BHL); and (iii) Microscopic Level at a control cabinet. Different data are available at different system levels. The former two are of a high level and the latter is of a low level. Loop fault detection at the high level is done usually through an analysis of aggregated data. Such approach is indirect, and shortcomings are obvious: (a) data aggregation in time and space would smear the faulty problem; and (b) a communication fault caused by data error/loss make it impossible to isolate the loop fault detection problem. Only the detection at the control cabinet level can directly detect the fault(s) in hardware and software, isolate them from the communication fault, and correct the faults permanently. In [16] we conducted (a) Systematic review of previous loop fault detection and data correction methods; and (b) Systematic classification of possible faults and causes in different levels.

A systematic approach for loop fault detection, maintenance and retrieving reliable data to support traffic operation, traveler information and Corridor Management is crucial. Communication systems are indispensible for data passing in data collection and integration for those purposes.

As shown in Figure 1.1, traffic data flow from loop circuit to PeMS/TMC data system: loop ➔ pull-box ➔ control cabinet with 170 + modem (30s data packets)➔ Tele-co line or wireless (up to 20 cabinet share one line) ➔ Front-End-Process (FEPT) of ATMS of District TMC ➔ PeMS.

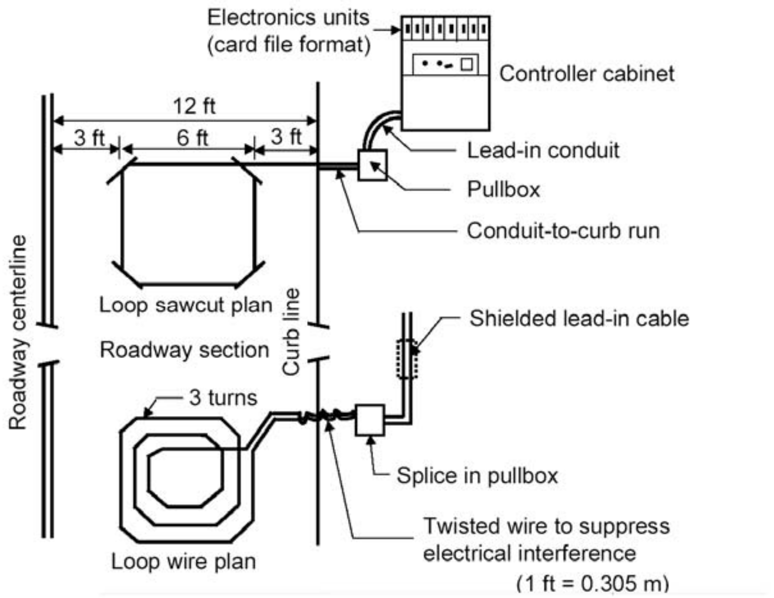


Figure 1.1. Loop detector system: loop circuit and connection with Controller Cabinet

1.1 The Problem

However, loop data are not reliable. The error in the loop data obtained at TMC may be caused by fault at any point or several points from the loop to the TMC database including from the communication system. According the Detector Fitness Program, loop detector system healthy conditions varies significantly from Caltrans district to district. The following faults often causes faulty traffic data from a viewpoint of higher level traffic monitoring system for a large area:

- Communication failure
- Systematic failures: Systematic differences in failure rates by freeway and by lane which could be affected by vehicle types;
- Electrical failures such as splicing problems or detector card faults;
- Synchronized failures: District-wide synchronized failures; e.g., unusually many loops in a District fail on the same day;

The following fault may appear in a mesoscopic level such as a stretch of freeway. A typical example is the Berkeley Highway Lab.

- Communication Down: No samples were received for the loop between 5:00 am to 10:00 pm;
- Mis-assignment: Mismatch between the real location and the location assigned in the map in control cabinet;
- Insufficient Data: PeMS receives too few samples to determine the loop health;
- Card Off: Too many samples have zero occupancy;
- High Occupancy: Too many samples with occupancy above 70%;
- Intermittent: Too many samples with zero flow and non-zero occupancy;
- Constant: The loop is stuck on a particular value;
- Feed Unstable: The detector failed in the past, and its current status can not be determined due to problems in the data feed;
- Correcting the data.

The problems to be looked at for on-site fault diagnosis tool at the control cabinet level are:

- No loop data;
- Chattering and misfiring;
- Cross-talk;
- Pulse duration error;
- Pulse break;
- Temporary inductance variation.
- Miss-assignment
- Sensitivity problem
- Loop detector card broken

Based on the higher level diagnosis, the Field Tool would check suspicious loops by comparing loop data with ground truth from independent sensors at control cabinet level. This will be able to exactly identify the problem.

1.2. Proposed Solutions

To eventually solve this challenge problem, it is necessary to take a systems approach. This approach is composed of three mutually complementary tasks: (a) loop fault detection (or diagnosis); (b) faulty loop data correction and missed data imputation; (c) loop detector system maintenance.

(a) Loop fault detection: How to efficiently and accurately detect and isolate the fault(s) in the loop detection system through data analysis and/or portable diagnostic tool working at the control cabinet level.

(b) Faulty loop data correction and missed imputation: How to temporarily correct/cleanse faulty loop data at different levels (traffic control cabinet, TMC) to maximally achieve reliable and accurate traffic data at TMC level with minimum time delay. If some data are missed due to any reasons, how to impute the data based some neighbor station data and/or historical data.

Detailed statistical analyses of time series data has been conducted from the PeMS and from the Detector Fitness Program to determine the *causes* underlying the failure symptoms from a macroscopic level.

This study would focus on developing an off-site fault diagnostic and data correction tool based on data analysis. Besides, it would look at the communication fault and make a recommendation as to which communication system is more reliable for Caltrans to adopt and how to improve its performance. The principle for developing an on-site fault diagnostic would include hardware and software: to compare synchronized loop data with ground truth from video cameras. The portable on-site loop detector fault diagnostic tool would be designed to achieve the following objectives: (i) on-site diagnosis of suspected mis-assignment problems, (ii) on-site diagnosis of suspected malfunctioning loops and determination of the exact fault location in the loop detection system, and (iii) on-site detector precision evaluation and calibration. The essential idea is to synchronize the ground truth measurement with the loop data and to compare the two data streams for diagnosis.

As listed in [16], the loop faults to be diagnosed at the microscopic level include hardware, software and installation problems, and loop card faults. Those faults appear as: *mis-assignment, temporary data missing, crosstalk, absence of data or constant for a period of time, broken cable, chattering, broken card, card sensitivity being too high or too low, broken pulse, mismatch of ON/OFF time instances between upstream and downstream loops for dual loop stations*.

This is the only level that one could conduct direct loop fault detection and isolate the loop faults from possible other system faults. Data in this level can either be the ones processed by loop detector card, which will be loop ON/OFF time instances or occupancies; or the raw loop pulse signal before the loop card. The main characteristics of those data are that (a) they do not pass any communication media and thus there is no possibility of communication fault which usually pollutes or loses the data stream; (b) all the raw information is available with a proper interface with the control cabinet; (c) real-time data are available; and (d) most importantly, an independent data source or baseline data could be obtained at this level thus loop fault detection could be conducted by comparing the loop detector reading with these data.

It is noted that only the fault detection at this level can be called direct and can be completely separated from communication error. It is also possible, only at this level, to identify all the loop faults and their exact causes. In addition, it is practical only at this level that one could use baseline data generated from independent sensor(s) for comparison in loop fault diagnosis. Besides, algorithms and code will be developed for data correct and imputation which may be due to temporary problems of the inductive loop system.

Chapter 2. Literature Review and System Analysis

This section is part of the deliverables as the document review part for period 1 and 2. This section focuses on the following points: (a) Systematic review of previous loop fault detection and data correction methods; and (b) Systematic classification of possible faults and causes in different levels. Although this review did not exhaust all the publications in this area, the reader could trace other publications further from the literatures reviewed. The objective this review is to find merits and weakness of those methods which will be used as the basis for the development of this project.

A systematic approach to detecting faulty loops is crucial to traffic operation, traveler information, and Corridor Management. Traffic detection systems are widely used for traffic management and control in California. The statewide *sensor system* consists of over 25,000 sensors located on the mainline and ramps, and grouped into 8,000 vehicle detector stations (VDS). Over 90 percent of the sensors use inductive loops. However, loop data are not reliable. The loop data delivered to TMC may contain error created at a point or several points between the loop detector and the TMC database, which presents a great challenge to loop fault detection. To solve this problem, it is necessary to take a systematic approach. This approach is composed of three complementary tasks: (a) loop fault detection; (b) faulty loop data correction/imputation; and (c) loop detection system maintenance. In our previous work [16], we categorized the loop fault detection approaches into three levels: (i) Macroscopic Level: such as the TMC/PeMS; (ii) Mesoscopic Level - a stretch of freeway such as the Berkeley Highway Lab (BHL); and (iii) Microscopic Level at a control cabinet. Different data are available at different system levels. The former two are of a high level and the latter is of a low level. Loop fault detection at the high level is done usually through an analysis of aggregated data. Such approach is indirect, and shortcomings are obvious: (a) data aggregation in time and space would smear the faulty problem; and (b) a communication fault caused by data error/loss make it impossible to isolate the loop fault detection problem. Only the detection at the control cabinet level can directly detect the fault(s) in hardware and software, isolate them from the communication fault, and correct the faults permanently.

Many methods have been adopted for fault detection and data correction/imputation for loop fault detection, and data correction/imputation. Different methods worked on different level of data in different ways. For example,

- Time aggregated data versus sub-second data
- At TMC level versus at control cabinet level
- Single loop stations versus dual-loop stations
- Synchronized adjacent lane data versus downstream/upstream data
- Historical data versus real-time data
- Raw loop data versus filtered/aggregated data
- Statistical methods versus deterministic filtering

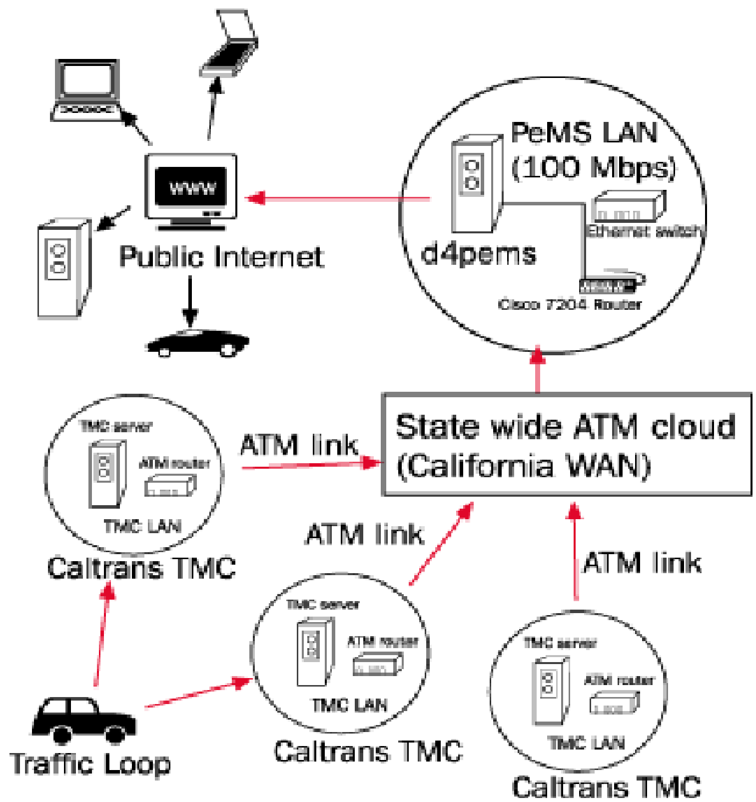


Figure 2.1. PeMS Structure in California

To systematically consider loop fault detection and data correction/imputation, it is necessary to diagnose possible faults at different level of the traffic monitoring system based on loop station. The overall picture for the data flow from individual loops to the TMC and PeMS in California can be described as: loop ➔ pull-box ➔ control cabinet with 170 + modem (30s data packets)➔ Tele-co line or wireless (up to 20 cabinet share one line) ➔ Front-End-Process (FEPT) of ATMS of District TMC ➔ PeMS. The system can be divided into three level: (i) Macroscopic Level: such as TMC/PeMS; (ii) Mesoscopic Level - a stretch of freeway such as Berkeley Highway Lab (BHL); and (iii) Microscopic Level, i.e. at a Control the cabinet. Different data are available at different system levels. For example, in California PeMS (Figure 2.1), 2Hz data is available at the TMC and PeMS level, which are aggregates into 5 minutes data.

Loop fault detection in mesoscopic and microscopic levels are necessary to produce good data quality in all levels, which is required by current and future traffic management and control, particularly, the new trend in the Integrated Active Traffic Management along a corridor. This systematic approach considers all the modes, all the roads in all the time for a transportation corridor. It is intended to develop a strategy to optimally management traffic for improved mobility, safety, emission, land use and energy use. The strategy would include different levels of management tactics which correspondingly needs different level of good quality data for support. Therefore, systematic sensor detection and data correction in all the levels are urgent and indispensible.

Systematic fault detection of the traffic monitoring system composed of loops needs the combination of diagnostics at different levels. As is shown in Figure 2.1, the traffic monitoring system has a hierarchical structure for data collection, processing and passing. Inductive loops and other sensors are in the lower level. Data analysis at any higher level through data analysis can only diagnose the loop fault indirectly. This is because the data fault at higher level may be caused by communication system or any other operation on the data. This also suggest that it is necessary to

(a) to distinguish data analysis and data correction at higher level from loop fault detection since they are indirect;
(b) using higher level data analysis to identify suspicious control cabinet which may have potential faulty loop stations;
(c) to diagnose higher level problems such as communication system, power down, or data acquisition system or software;

(d) to combine higher level data analysis with lower level (onsite) loop fault detection using Portable Tool.

The error in the loop data obtained at TMC may be caused by fault at any point or several points from the loop to the TMC database: physical loop, connection of the loop and the control cabinet, loop card including sensitivity, traffic data (occupancy, count, speed) estimation method from the pulse signal, communication media between control cabinet and TMC. It can also be envisaged that data analysis at any point other than the control cabinet can only indirectly diagnose the loop fault in the sense that faults at higher level would interfere with fault loop data analysis. Thus those methods claimed for loop fault detection based faulty loop data analysis are essentially fault diagnosis of the monitoring system, which can be called *indirect methods.* Only those methods or tools used at the control cabinet level can be called *direct methods*. Direct detection must be performed by a *portable tool* at the control cabinet level, which needs to have the following functions:

(a) to generate ground truth based on some independent sensor;

(b) to synchronize the detection of the loops connected to the control cabinet with the ground truth detection;

(c) to compare the loop data with ground truth for diagnosis.

This section classifies and reviews previous study on faulty loop data analysis and loop fault detection at different levels of the system, which corresponds to using different level of aggregated data. Since data correction/cleansing and imputation are usually closely related to data analysis and detection, they will be briefly reviewed and classified in parallel. Previous work on loop fault detection and data correction/imputation can be divided according to the data levels: macroscopic, mesoscopoic and microscopic.

A systematic literature review on loop fault detection through faulty data at different aggregation level was conducted in [16]. The characteristic of this approach is to apply various statistical analysis methods to the aggregated loop data to figure out possible faults in the loop detection system. Since most previous approaches are indirect, the faults that can be detected are usually large scale problems such as electric or communication system faults. These cannot tell exactly what the fault is, appearing at which point of which loop detection system. This is one of the limitations to the macroscopic and mesoscopic approaches. Besides, communication faults are tangled with the loop detection system fault. In the rest of the section our document review will be focused on the low level loop fault detection.

2.1 Loop Fault Detection at Macroscopic Level

Typical example is the PeMS level or Caltrans District TMC level, which provide 30 second and 5 minute aggregated data. Each Caltrans District is composed of multiple highway corridors. The main characteristics of those data are that (a) they are the data practically used for traffic management such as ATMS and control; (b) heavy data aggregation are usually involved; (c) those data usually need to passes long distance communication media to reach PeMS/TMC; (d) the data will be subject to small time delay due to data processing and passing through the communication.

PeMS data DSA (Daily Statistics Algorithm) checking for data errors [2]:

- The number of samples in a day that have zero occupancy must be less than a certain threshold;
- The number of samples in a day that have occupancy greater than zero and flow equal to zero must be less than a certain threshold;
- The number of samples in a day that have occupancy greater than a certain value (PeMS uses 35%) must be less than a certain threshold;
- The entropy of occupancy samples must be greater than a certain threshold.
- The definition of entropy is:

$$E = \sum_{x:p(x)>0} p(x) \cdot \log\left(p(x)\right)$$

The idea is that constant value of flow will lead to low entropy. Thus entropy could be used to detect if the detector has constant value consistently.

[26] used adjacent loop point flow for comparison to detect possible erroneous data. It used the ratio of flows of upstream and downstream stations as the measure for test. The reason is that: for

the some time t, the upstream and downstream have completely different clusters of vehicles. For free-flow traffic and 10-minute aggregated data, this makes sense.

Work in [2] is a systematic work in data based fault detection focusing and on how to correct the data for the following two cases: data missing and bad data. It also proposed method for data correction. [19] used ARMA model for prediction of loop data, which was over time and could be used for fill in faulty data. But [2] commented that that its response was too fast. It suggested using good neighbor (same location but different lanes, or adjacent locations) data for patching the wholes. Averaging or interpolation over space methods were used for filling the whole. The mathematical foundation for this method was that occupancy and flow of neighbor loops were highly correlated. However, if several loop stations were down in a section of freeway, this method mould become questionable. The algorithm developed in [2] is called Daily Statistics Algorithm (DSA) since it produces only one result using a whole day 30s q (volume) and k (occupancy) data: good or bad on that day. The Detection criterion is based on the value of 4 statistic parameters and the selected threshold. Each statistic parameter targets for one error type.

The main used in methods used [2] for data correction was to look at neighboring loops in adjacent lanes and/or up/downstream as well as historical data:

- Linear interpolation overtime of the loop itself
- Linear interpolation over space of neighboring loops
- Averaging overtime of the loop itself
- Averaging over space of neighboring loops
- Combinations of them all – in fact, averaging is a special case of interpolation

This method could not distinguish the case of temporal loop failures since the statistic over a whole day will not tell temporal behaviors. The proposed method used threshold to identify 4 types of loop data errors:

- Occupancy and flow are mostly zero
- Positive occupancy and zero flow
- Very high occupancy
- Constant occupancy and flow

This has been achieved by classify a fixed loop daily data into 4 categories and then aggregate over time. Then threshold is defined for such error identification, which is based on some common knowledge. Those methods could not be used for the following faulty loops:

- Permanent isolated fault loop
- Temporal faulty data: such as those cases which are affected by weather and heavy traffic
- Individual loop fault such as sensitivity, crosstalk, etc.

This algorithm has been used in PeMS for several years. It proved to be reliable and better than other methods for higher level aggregated data for some larger range and or longer time loop problems.

Data correction methods were also proposed in [20], which was basically using historical data as well as adjacent station data for interpolation over distance and time. A Kalman filter is also designed for estimation of lane volume to filter out measurement noise. The filter performance showed that it was unbiased with discrepancy of 300vhr.

In the work of [26], Poisson distribution was used to describe the probability for the number of vehicles counted (flow) at a loop station every 30s interval.

$$p(y) = e^{-\mu} \frac{\mu^y}{y!}$$

$y-$ point flow: vehicle count at a given loop station. The probability for *n* continuous reading of a flow *y* was:

$$p^n(y) = e^{-n\mu} \frac{\mu^{ny}}{(y!)^n}$$

Then a threshold was set for data error checking: $p^n(y) \le P_{\min} = 0.0005$. An accumulated Poisson distribution should be used to represent the point flows at a loop station.

$$P(0 < y \le x) = \sum_{y=1}^{x} e^{-\mu} \frac{\mu^y}{y!}$$

Due to the stochastic property, the point flow y could be quite different for different traffic situations: AM peak, PM peak, off-peak, congested and non-congested cases. This idea is quite different from the entropy test of PeMS where constant flow will lead to very low entropy. This means that low entropy corresponds to invariance of traffic flow, which can happen only if the loop has faulty reading.

Time-of-day flow and occupancy ratio were used reflect vehicle types such as trucks and passenger cars [26, 8]:

- This ratio could assume any value;
- Trucks corresponds to low flow and high occupancy
- Passenger cars the other way around in the same time period
- Low flow and high occupancy may indicate congested traffic in another time period (cause by AM peak, PM peak and incident/accident)

[28] used loop data to calculate average vehicle length: 2.7m~18.0m. This threshold is used for data error checking. It is obvious that such check can only tell if the data is reasonable or not. It could not tell what was wrong exactly with the system.

The Detector Fitness Program (DFP) [25] looked at the loop station in 3 Caltrans District: D4, D7 and D11. It defined some measurement parameters. 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. The evaluation method first uses PeMS 30s data. 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. *Fault States* looked at included: *line down, controller down, no data, insufficient data, card off, high value, intermittent, constant value,* and *feed unstable*. Detection methods involved was mainly *Data Threshold Checking*. This work also looked at the possible higher level fault caused by communication systems involved in data passing for TMC/PeMS, which include: Caltrans owned fiber optics, wireless GPRS modem (UDP, TCP), telephone line and wireless cell-phone lines. The main idea is to tell if the communication system is healthy from the status of all the loop data related to the same communication system such as those belonging to the same control cabinet.

Summary: The problems to be looked at for macroscopic data analysis are:

- Communication Down: No samples were received for the loop between 5:00 am to 10:00 pm;
- Insufficient Data: PeMS receives too few samples to determine the loop health;
- Card Off: Too many samples have zero occupancy;
- High Occupancy: Too many samples with occupancy above 70%;
- Intermittent: Too many samples with zero flow and non-zero occupancy;
- Constant: The loop is stuck on a particular value;
- Feed Unstable: The detector failed in the past, and its current status can not be determined due to problems in the data feed;
- Systematic failures: Systematic differences in failure rates by freeway and by lane which could be affected by vehicle types;
- Electrical failures such as splicing problems or detector card faults;
- Synchronized failures: District-wide synchronized failures; e.g., unusually many loops in a District fail on the same day;
- Indentifying suspicious loops

Methods used at this level for direct loop fault detection include: (a) statistic, (b) Entropy, (c) threshold checking based on some known physical limits and empirical values, and (d) Comparing with neighboring (adjacent lanes, upstream/downstream) stations.

Method used at this level for data correction/cleansing/imputation include: to omit unreasonable data based on some threshold; linear interpolation or moving window averaging over time, space (adjacent lanes, upstream and downstream)

2.2 Loop Fault Detection at Mesoscopic Level

System in this level involves a section of freeways which has more than one control cabinet with multiple loops. The characteristics in this level are:

- Sub-second data of each are available;
- Loops connected with the same control cabinet are time synchronized;
- Loops connected with different control cabinets are time synchronized;
- Minor communication system is involved in data synchronization and data passing.

Thus the communication system fault can be easily determined by some simple ad hoc method such as check sum. In this way, the communication system fault could be isolated from the loop fault.

Berkeley Highway Lab (BHL) is a typical example of such system. BHL has 9 loop stations with 164 loop detectors for both side of Interstate I-80 between Gilman St. and Power St. Figure 2.2.

Work in [17, 18] considered loop fault detection systematically based on BHL system. A two-level, nine diagnostic scheme has been developed including dynamic diagnostics based on speed and vehicle composition. The developed algorithms were implemented software and currently running in BHL system. This work separated *detector deficiencies* and detector fault. The fault detection system used 1/60s data from loop, which were basically some threshold tests:

- activity test: test criterion: continuous 15 minute constant signal;
- Minimum on-time test for at least 100 vehicles (fail criterion: 5% vehicles occupancy < 8/60s);
- Maximum on-time test for at least 100 vehicles (fail criterion: 5% vehicles occupancy > 600/60s);
- Dynamic Minimum/ Maximum on-time test: similar to minimum/maximum adjust those time interval test threshold based on speed and vehicle length;
- Minimum Off-Time – If 5% or more of the off-times in a sample of 100 vehicles are less than 25/60 seconds, the test fails;
- Dynamic Maximum Off-Time – This is one of the new diagnostics. If 5% or more of the off-times in a sample of 100 vehicles are greater than a threshold value which is a variable depending on the calculated average time headway, the test fails;

- Mode on-time test: test for 1000 vehicles; Test criterion: calculate mode of the distribution is outside of the interval [10/60s, 16/60s];
- Dual loop on-time difference test: test for 1000 vehicles; Test criterion: if the difference between the Upstream and downstream loop is outside the time interval [-3.5s, +3.5s]; it only valid in free-flow condition; not well-designed yet;
- Refining those tests in two aspects:
  - o Predicting that the detector passes the tests when in fact the detector data is not good
  - o Predicting that the detector fails the tests when in fact the detector data is good.

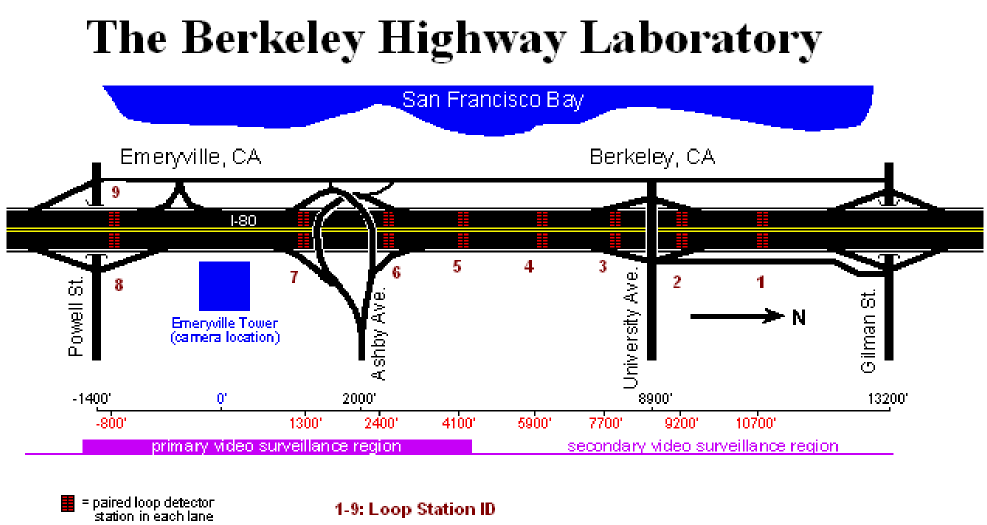


Figure 2.2. Berkeley Highway Lab

The test fail will need to account for the situations when there is little traffic such as in the early morning. This study also identified that some data problems are due to Verizon CDPD modem network connection instead of loop stations faults, which means that the communication fault could not fully separated. It indicated the necessity of direct loop fault detection at control cabinet level.

This work recognized the importance of using low level sub-second data instead of aggregated data. Conventional traffic monitoring aggregates the event data to fixed period samples of flow, velocity and occupancy before transmitting the data to the Transportation Management Center

(TMC). The sampling period is typically on the order of 30 sec or 5 min. This relatively coarse aggregation can obscure features of interest and is vulnerable to noise. Both of these factors delay the identification of resolvable events, the former due to the need to wait until the end of a given sample period and the latter due to the need to wait for multiple sample periods to exclude transient errors. The Nyquist sampling criteria from basic signal processing dictates that one can only resolve features that last two sampling periods and the need to tolerate noise in the measurements further reduces the response time. As such, it is necessary to have a trade off between cost and data passing frequency. This study also suggest to pass al the event (low level sub-second) data to MTC as well as all the data processing. It mentioned that link travel time for BHL is based on vehicle re-identification.

A methodology for substituting for missing data (imputation) was also developed in [18]. The missed data is imputed based on the data of adjacent lanes using interpolation.

Work in [21] also looked at 20s and 5minute data. The work used reasonable interval for flow density and speed to test if the data were reasonable: if they fell into the interval, then they are considered good data. Otherwise, they were considered bad data. The thresholds of those intervals were specified based on experiences on historical data. Similar idea was used for *k*-*q* plane for specifying a criterion region by [11]. The boundary of the region is determined by some parameters which need to be calibrated according to the site situation. This idea is slightly better because the relationship between *k* and *q* is taken into consideration. However, they did not take the advantage of using historical data as well temporal data relationships in detection and correction. [2] indicated that those methods were difficult to use in practice since the thresholds were difficult to calibrate. Due to those factors, several situations were incorrectly detected: false positive and false negative happened.

[20] uses FSP data which is composed of three parts: loop detector data, probe vehicle data and incident data of approximately two months. The loop detector data includes 30s data and 5 min aggregated data for data error checking. The loop locations are divided into mainline, HOV lane and on-ramp, which have different traffic characteristics. 14 error checking criteria based on the two types of data sets are proposed. Parameters taken into consideration are volume, occupancy

and average speed. The data needs pass 10 consecutive tests. Those checks include bounding checking – traffic parameters must be within certain physical bound; contradictory check – two traffic parameters such as occupancy and value, occupancy and speed from the same loop station must be consistent. The seriousness of erroneous data have been analyzed according percent of time in malfunction, percent of station and percent of time in malfunction, etc. It has been found that data missing is the most significant error which appeared for blocks are sensors/stations. This may suggest that such error is caused by data transmission or communication system. It was found that for I-880 FSP data, malfunction stations are about 21% on average even the stations are well-maintained for proper function.

Summary: Highway Section/Corridor: Typical example is the data from Berkeley Highway Lab. In this level, 60Hz data is available every second. The characteristics of those data are that (a) sub-second data could be obtained at this level; (b) time synchronized sub-second data are available for loop stations on a stretch of highways; (c) only a short distance communication system is involved; (d) the detection could be near real-time in the sense that the time delay for data passing were in the level of few seconds. Besides hardware and software problems, other loop faults looked at this level include: *mis-assignment, temporary data missing, crosstalk, no data or constant for a period of time, broken cable, chattering, card broken, card sensitivity too high or too low, pulse broken, mismatch of ON/OFF time instant between upstream* and *downstream loops for dual loop stations, and indentifying suspicious loops.*

Methods used for direct loop fault detection include: analyzing sub-second data, threshold checking, and vehicle re-identification. Method used at this level for data correction/imputation include: linear interpolation or moving window averaging over time, space (adjacent lanes, upstream and downstream). It is noted that even if in this system level, some detailed loop fault still cannot be detected. He advantage for such system is that one could compare the synchronized upstream station and downstream station data for diagnosis and data correction which could not be achieved at control cabinet level.

2.3 Loop Fault Detection at Microscopic Level

Many operating agencies use specialized loop testers to assess the quality of the wiring [12, 10], but these tools bypass the controller and loop sensors; thus, they do not analyze the entire detector circuit, nor do they analyze the circuit in operation. To this end, most operating agencies employ simple heuristics methods such as if the loop sensor indicator lights is on as a vehicle passes. Such tests are typically employed when the loops are installed close to the control cabinet. Many practitioners and some researchers [11, 6, 19] have worked to formalize the latter heuristic by looking at if the time series 30 second average flow and occupancy within statistical tolerance.

Low level loop data correction could be trace back to the Freeway Service Patrol study in 1990s [22, 27]. It looked at the transition times in sub-second of dual loop stations with 20ft distance between upstream and downstream loops. It noticed some problems in low level data including:

- data missing
- un-matching of those data which results in unreasonable occupancy and speed;
- on-time and off-time are not always related;
- no-flow and no-speed but with positive occupancies;
- existing pulses in both up and down streams

The author mentioned that some of the phenomenon could be explained as caused vehicle changing lane. However, there is no systematic diagnosis in [22] for loop fault, nor systematic methods for lower level data correction.

In [3], Chen and May considered fault detection problem for a single loop. It used the number pulses as the vehicle counts to verify loop data. If pulse broken, it would cause the data problem. It developed automated loop fault detection system which uses aggregated data. They must accept a large sample variance and potentially miss problems altogether. For example, the systems have to tolerate a variable percentage of long vehicles in the sample population. Their methodology examines the distribution of detector *on-time*, i.e., the time the detector is occupied by a vehicle. Unlike conventional aggregate measures, their approach is sensitive to errors such as "pulse breakups", where a single vehicle registers multiple detections because the sensor output flickers off and back on. This is the main disadvantage to use vehicle count forma single loop for fault detection: one cannot isolate other loop fault from the pulse flickering problem.

Studies in [7] use dual loop information for comparison to detect loop fault. It focused on evaluation of loop sensors and detection of cross-talk. It was developed for off-line data analysis but could possibly be used for on-line in the future. It can be summarized in three steps:

(i) Record a large number of vehicle actuations during free flow traffic;

(ii) For each vehicle, match actuations between the upstream and downstream loops in the given lane;

(iii) Take the difference between matched upstream and downstream on-times and examine the distribution on a lane-by-lane basis. Assuming the loops are functioning properly, only a small percentage of the differences should be over 1/30 seconds. Otherwise, “Cross-talk” fault is announced.

Using dual loop speed traps to identify detector errors is another approach conducted in [7]. At free flow, on-time difference and off-time difference should be the same if no hardware problem. So if they are not the same, there may be hardware and/or software problem. But this is not true if it is not free-flow speed.

About Loop Data Correction/Cleansing in Microscopic Level

In [22], Karl Petty analyzed the situations of data loss of both upstream and downstream detectors and the mismatch between them which lead to error in vehicle counts, speed and occupancy. Some preliminary correction methods for post-processing were proposed for vehicle counts and occupancy. The method was to use the data for least square fitting to get the occupancy trajectory over time. Then the incorrect or missed occupancy value could be inferred from the Least-Square fitted trajectory. For count correction, it is a high level approach by using the law of conservation of vehicle numbers in main lanes, onramps and off-ramp.

[9] considered even based traffic data validation for selected 5 different loop detector cards. The purpose is to compare the performance of those cards under similar circumstances using even data including measurement accuracy and flaws such as data error caused by cross-talk. The method is to set up eight criteria for testing the data over 24 hours. Those criteria are based on some common sense of vehicle behavior, loop detection system characteristics, and traffic state parameter. Of the eight test criteria, five apply to single loop detectors and all of them apply to dual loop detector. Here even data means the lower level data from sensors without aggregation as those of BHL data which has 1 minute update rate with *60Hz* information.

The Advanced Loop Event Data Analyzer (ALEDA) system developed by the Smart Transportation Applications and Research Laboratory (STAR Lab) of the UW, is a plug and play system for detecting and correcting dual-loop sensitivity problems based on loop event data and has been applied for improving dual-loop data [4, 5]. The specific problem focused there is loop sensitivity. It was claimed that an adaptive method has been developed for changing the loop card sensitivity. In fact, the sensitivity problem only exists for Reno 222 detector card which needs manual adjust the sensitivity to different level by traffic engineers. For other smart card such as 3M Canoga car or IST card, the sensitivity is automatically adjusted. This has been proved by some experiments conducted in this project.

Summary: This is the only level traffic engineers could conduct direct loop fault detection and isolate the loop faults with possibly other system faults such as data loss/pollution through wireless communication. Data in this level can be either data processed by loop detector card, which will be loop ON/OF time instant or occupancy; or the raw loop pulse signal before the loop card. The main characteristics of those data are that (a) they do not pass any communication media and thus there is no possibility of communication fault which usually pollute or loose the data stream; (b) all the raw information is available if proper interface with the control cabinet is available; (c) real-time data are available; and (d) most importantly, ground truth could be obtained at this level thus loop fault detection could be conducted through comparison between the loop detector reading and the ground truth.

Loop faults to be look at the microscopic level include any loop card faults: *mis-assignment, temporary data missing, crosstalk, no data or constant for a period of time, broken cable, chattering, card broken, card sensitivity too high or too low, pulse broken, mismatch of ON/OFF time instant between upstream* and *downstream loops for dual loop stations*.

Methods used at this for direct loop fault detection include: using 60 Hz data, using pulse signals which is by pass loop card. Systematic data correction/imputation in this level have not been well-developed and documented yet.

It is our opinion that high quality of data is absolutely necessary for all level of application in Active Traffic Management and Planning. Such data would require high quality basic sensor data and reliable communication system. Data quality from sensors depends on two factors:

- sensor detection system working condition
    - normal mode
    - error mode
        - persistent error caused by sensor system fault
        - intermittent error caused by sensor measurement noise
        - external uncertainty such as vehicle relative location to the sensor
- sensor characteristics
    - sensor measurement noise/error compared to ground truth
    - physical mechanism and its limit
    - environmental condition effect

To have a accurate and reliable data detection system, it is imperative to develop and build the following functions in the system:

- automatically detect/isolate the detector fault and its location as quickly as possible
- automatically correct the error by some software approach if possible
- establish a systematic sensor detection system maintenance regulation and implementation mechanism
- field operation to detect and correct those error that could not be detected, isolated, or corrected only from data side and by software.

Besides, it is also noted that data processing method to estimate the relevant traffic parameters from the basic sensor data also affect the estimation error which traffic engineers should also pay attention to.

In this sense, data quality largely depends on the quality of lower level sensor data. If the basic sensor data reading has a high quality, and if the data processing for traffic state parameter estimation in all the application levels are appropriate, high quality application data can be generated. The sensor detection and data correction strategies developed in this project is for this purpose.

Chapter 3. Portable Loop Fault Diagnosis Tool Development

This chapter presents preliminary results in the research and development of a Portable Loop Fault Detection Tool for use at the control cabinet level. This work is complementary to most previous work focusing on macroscopic faulty loop data. Part of the project is to develop a real-time vision-based multi-lane multi-vehicle tracking algorithm for freeways to use as baseline measurements to compare with the lower level loop signal for direct loop fault detection. The system is primarily developed for both freeways and arterials. It is composed of a mobile trailer, a retractable pole with a video camera mounted on top to look at the suspicious loop detector on the ground, a computer running the vehicle tracking algorithm, and another computer at the control cabinet interfacing with a loop detector card though RS232 serial port. Both computers run IEEE 802.11b wireless for information passing and synchronization. A small data packet of the virtual loop information passes from the trailer computer to the cabinet computer through a UDP protocol. Information from the virtual and the physical loops are then compared which can be viewed on a visual display. Preliminary tests have been conducted and the results are analyzed. The chapter is structured in a following way: Section 2 is for the overall system structure; Section 3 is for the algorithm and the system development; section 4 presents some experimental work; and Section 5 is for concluding remarks and future work.

3.1 Development of Portable Loop Fault Detection Tool (PLFDT)

The PLFDT (Figure 2.1) is designed for systematic loop fault detection at the control cabinet level. A loop detector(s) could be identified as being *suspicious* from a higher level data analysis in TMC/PeMS. The suspicious loops will then be diagnosed further using the portable tool. The tool will enable the operator to use independent stream of traffic measurements for comparing with the suspicious loop detector data. This portable tool will be designed to achieve the following objectives:

- determination of the exact fault type and causes in the detection system
- on-site diagnosis of faults on:

- o mis-assignment
- o malfunctioning such as misfiring
- o inappropriate card sensitivity settings
- o inductance variation due to temperature and humidity
- o broken loop circuit due to
  - ▪ improper installation
  - ▪ road surface maintenance
  - ▪ fatigue

- facilitating on-site detector precision evaluation and calibration.

3.2 Overall System Structure of PLFDT

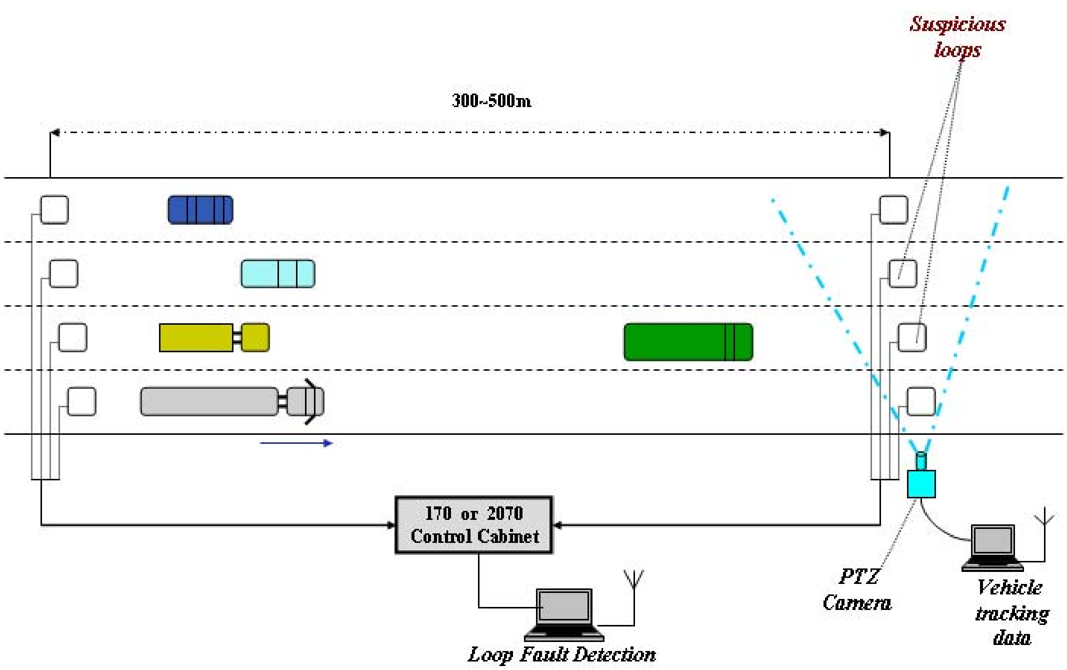


Figure 3.1. Overall PLFDT system structure

The system development includes hardware, software and algorithm development. Our hardware setup consists of the following components (Figure 3.1):

- Mobile trailer which can be towed to the site near the suspicious loop location
- Retractable pole with a PTZ (Pen-Tilt-Zoom) camera mounted on it

- Two laptop computers with the Linux operating system
- *Computer A* to capture video images, process them in real-time, and send out the result via IEEE 802.11b wireless
- *Computer B* to interface with a loop detector card, receive the video processing data from Computer A through IEEE 802.11b wireless, and compare the synchronized signals for loop fault detection;

3.3 Mobile Pole for Roadside Video Camera Mounting

A mobile pole for the roadside camera setup has been developed (Figure 2.2).

Figure 3.2. Video Camera Mounting on Mobile Trailer: Left: Mobile retractable pole; Upper right: PTZ camera on top for looking at the loop and for vehicle tracking to obtain baseline data; Lower right: video computer also running IEEE 802.11b wireless communication using USB port.

The mobile trailer has four retractable folding legs for supporting the platform for leveling. It has several extra supports for robustness if necessary. The mast on the mobile platform can be retracted and folded for easy movement of the trailer. The pole can reach up to 60ft high (Figure 3.2). On the side of a freeway, camera mount on top can have a good view angle over a 6-lane freeway traffic.

The Pen-Tilt-Zoom parameters can be controlled using the remote controller or using a control software running under Microsoft Window System through the RS 232 serial port interface. This setup process is necessary for the camera to view the loops on the ground and to display on the computer screen so that a virtual loop can be overlaid on the actual loop.

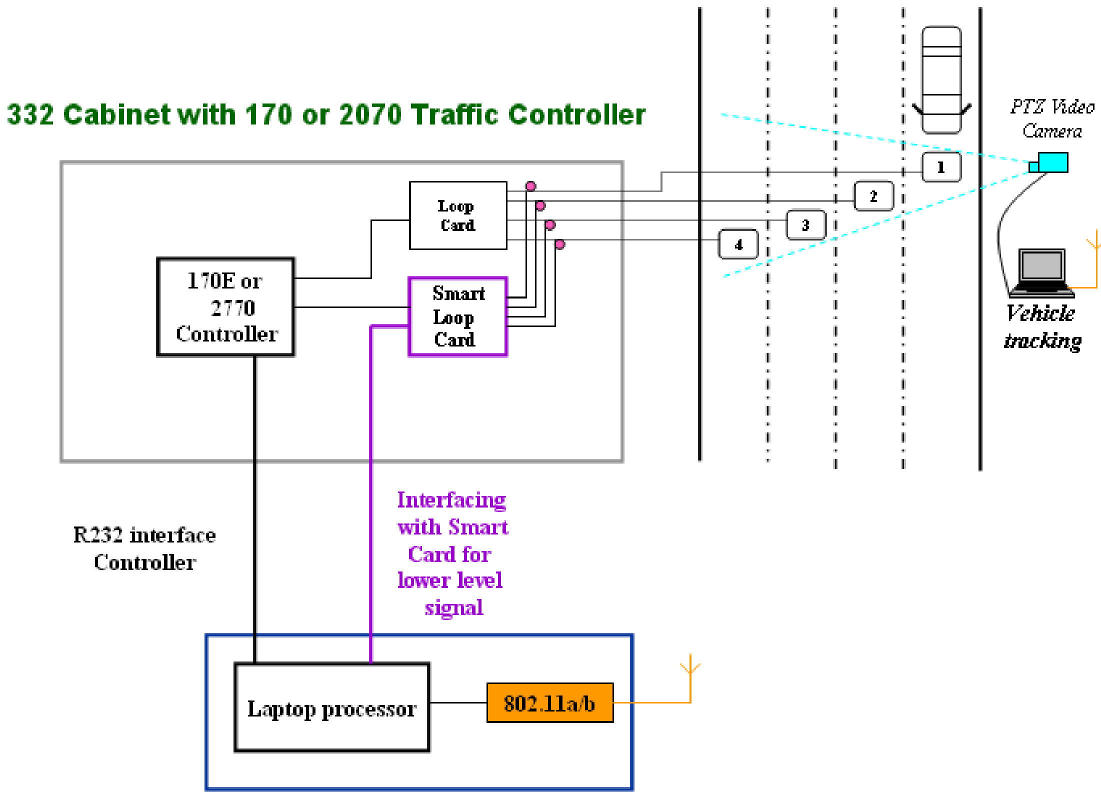


Figure 3.3. Interfacing with control cabinet and smart card

3.4 Interface with Control Cabinet

A loop card receives raw analog signals from each loop circuit, processes them with a physical oscillator and amplifier, and outputs traffic signals. Loop cards can be divided into two types: single-layer and multi-layer output cards (Figure 3.3). Single-layer output cards have only two outputs -- the vehicle count (volume) and occupancy – which are results of processing the input signal from the loop circuit. For example, Sarasota GP5 and Reno 222 cards are single-layer output ones that are widely used. There is no direct interface port with these cards. Instead, their signals are directly fed into the controller. The output form the card to the controller is either 1 or 0 without the lower level signal available. The low level signal is more attractive than the binary data for several reasons: (a) it can be used for extracting vehicle signatures for re-identification; (b) it tells if the sensitivity of the card is properly adjusted; (c) it tells if any algorithm in the card has a flaw; and, (d) most importantly, we can remove time delay incurred in the traffic controller. Multi-layer output or *Smart* Cards, such as the 3M Canoga and IST cards, have multi-level output information including the start detection times, the occupancy, the vehicle count, fault status, and even the inductance intensity signals calculated from the frequency. A smart card has a built-in RS232 interface port, and thus lower level signal can be obtained. We chose a smart card, 3M Canoga C922, which is compatible with 332 Traffic Control Cabinets and both 170 and 2070n controllers, for our current development. The update rate for the 3M Canoga C922 card is 13Hz.

The link on the side of the laptop is UPS connection which applies to most laptop computers.

However, most loop detector card used on freeways on Reno 222 cards. Those cards are designed very simple without interface port. To solve this problem, a C1 Connector has been modified to retrieve information from the 170 Traffic Controller as shown in Figure 3.4. The C1 Connector has 104 pins which passes signals between the 170 Traffic Control and the cabinet including processed traffic state parameters such as occupancy and traffic light control signals. However, the raw signals from the loop circuit are not connected to those pins.

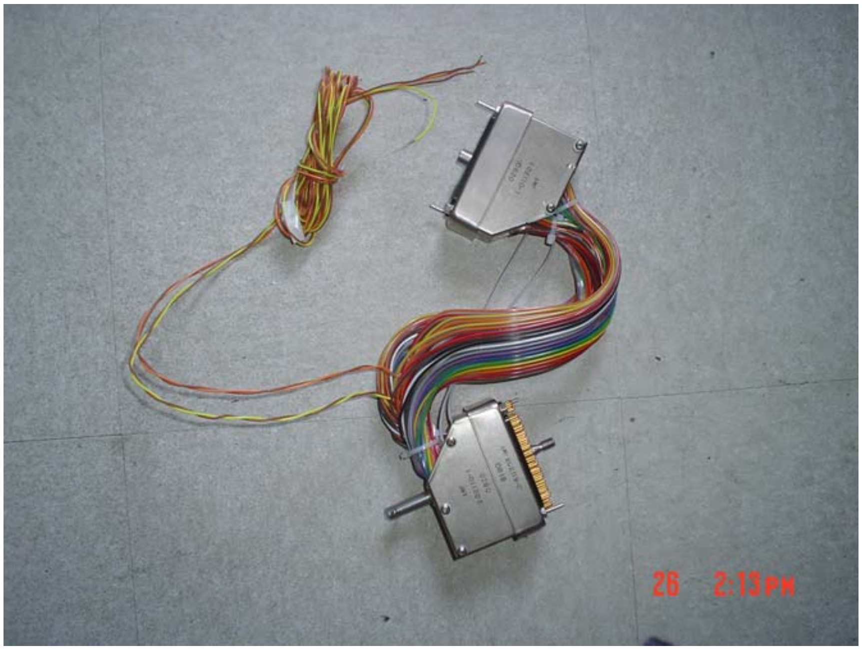


Figure 3.4. C1 Connector between the Control Cabinet and the 170 Traffic Controller

*A 3M Canoga 922 card was connected to a 322 traffic control cabinet to read the raw loop ind*uctance data directly from the physical loop, as shown in Figure fff07-(a). It also transfers these loop information to the Laptop through the RS-232 serial cable as shown in Figure fff07-(b). The 3M Canoga 922 card could read at most two physical loops at the same time.

Figure 3.5. Laptop using RS232 serial interface with C922 3M Canoga Card

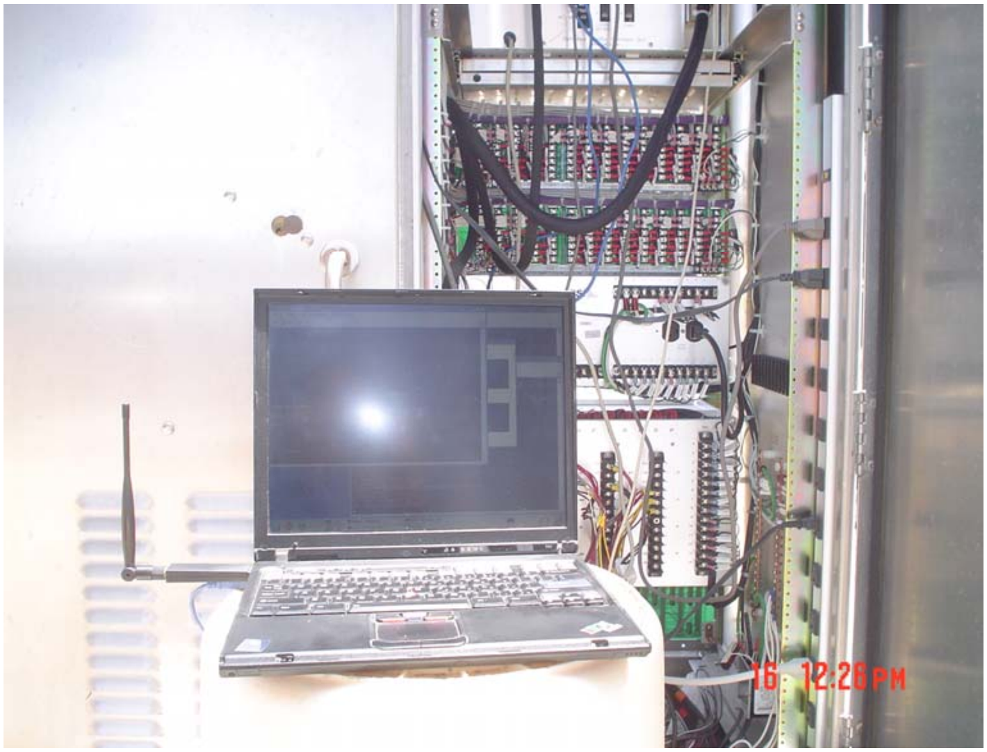


Figure 3.6. Laptop interfacing with C922 3M Canoga Card also run IEEE802.11b wireless communication handshaking with the laptop computer running video camera

3.5 Computer Vision System

On the other side, the vision system was set up as illustrated in Figure 3.2 (a). The camera was mounted on the top of the trailer pole to look downward towards the loop detectors at the RFS test intersection. The camera's intrinsic parameters were estimated by using the Camera Calibration Toolbox for Matlab® (http://www.vision.caltech.edu/bouguetj/calib_doc/). The extrinsic parameters are estimated by a simple external calibration algorithm which uses a single rectangle [15]. USB 300mW WiFi adapter with 9dBi and 5dBi antennas were used for reliable wireless communication with about 800m distance coverage.

3.5.1 Real-Time Multi-lane Vehicle Tracking Algorithm

We have designed a computer vision system to obtain baseline measurements to compare. The whole system consists of three parts:

- a camera (Canon VC50i pan-tilt-zoom communication camera);
- a moving platform; and
- a Linux-based video processing software

The Canon VC50i camera provides a wide range of view by panning through a broad reach of 200 degree, tilting of 120 degree, as well as a 26x optical zooming. It provides superior camera optics that a good quality of images can be obtained even with challenging illumination conditions, such as strong shadow cast that causes too high image contrast. An Intel Pentium Core laptop computer equipped with a USB frame grabber was used for video data processing.

There are many commercial vision-based vehicle detection systems ("virtual loop detectors") also available. However, most virtual loop detectors are based on the background subtraction algorithm. They normally use frontal-view video images to avoid difficulties caused by occlusions and to get better lane positioning. Since our application requires the camera on the roadside, it is difficult to adopt those systems.

A video processing algorithm has been developed to detect and track vehicles in multiple lanes at the same time. The algorithm combines the background subtraction algorithm with the feature tracking and grouping algorithm to better handle the occlusion problem. The developed algorithm is more robust to shadow and occlusions than conventional virtual loop detectors and, thus, better separates between lanes. An example detection result is shown in Figure 3.7. We see that the upper-left background subtraction result cannot separate the vehicles in multiple lanes but the newly developed algorithm can correctly localizes them.

An example placement of a "virtual loop" over the loop mark on the ground is shown in Figure 3.8. The trajectories of all the vehicles in the image are estimated, and the virtual loop is triggered by analyzing the trajectories.

The software was developed under Linux environment using the OpenCV library. The algorithm runs on a Pentium Core processor (1.83GHz) in real-time at 10 fps. The details of the image processing algorithm are described in [14].

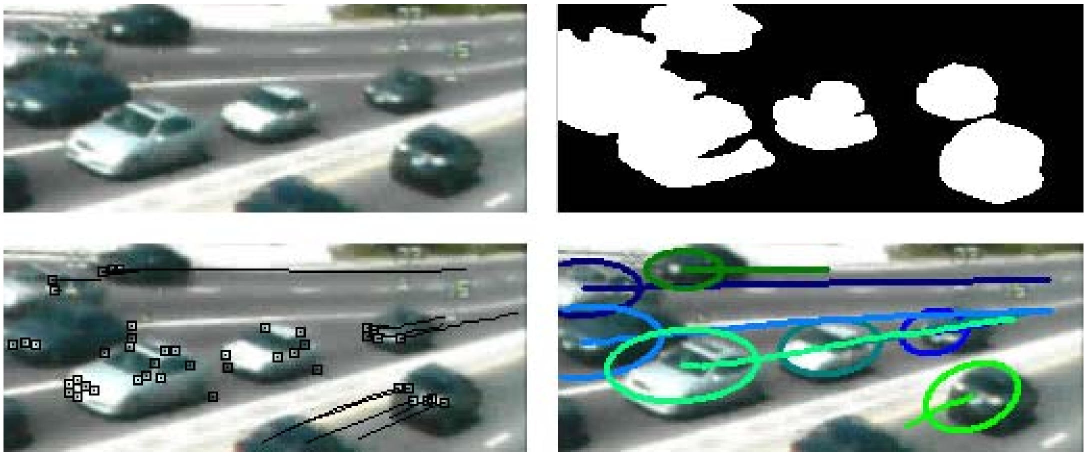


Figure 3.7: An example feature tracking. Upper-left: the original video image; Upper-right: the 'background subtraction' cue where the four vehicles in the left are detected as one big region; Lower-left: the feature detection and tracking cue; Lower-right: result by combining the background subtraction cue and the feature detection and tracking cue.

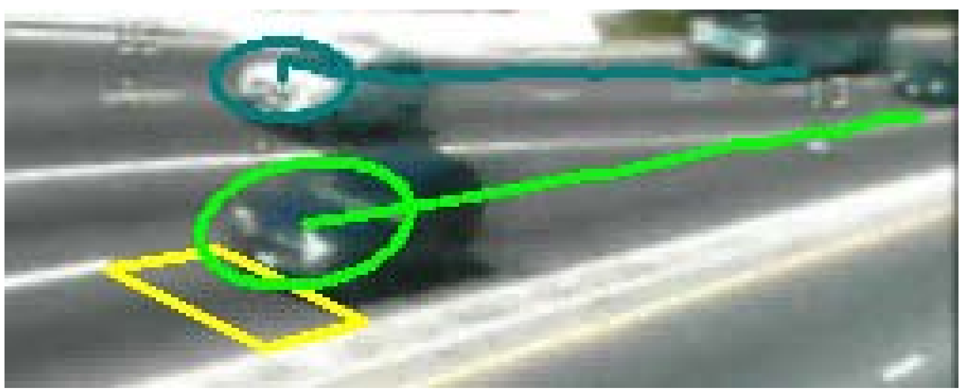


Figure 3.8: Flashing of the virtual loop is triggered when a vehicle trajectory reaches it

The 10Hz update rate is frequent enough to avoid any missing vehicle count due to high vehicle speed. For example, when a vehicle moves at 70mph or 31.3 m/s, and loop length 2m and vehicle length 4m, the total crossing length for a vehicle starting on upstream edge and leave at downstream edge is: $2+4=6m$. Thus the expected duration is $10.0/31.3=0.192s$. If the video camera update rate is 10Hz, there are at least one or two frames of the video where the vehicle is on the virtual loop. In addition, even if a fast vehicle passes through the virtual loop in between the frames, we can still infer vehicle's passage by analyzing the continuous trajectory that the vision algorithm provides.

3.5.2 Detection Software Development

The software has the following three components:

- High precision synchronization of the timers on the two computers through wireless communication
- Real-time multi-lane and multi-vehicle tracking using the video camera, and
- Matching signals from the two data streams,

which are described respectively in this section.

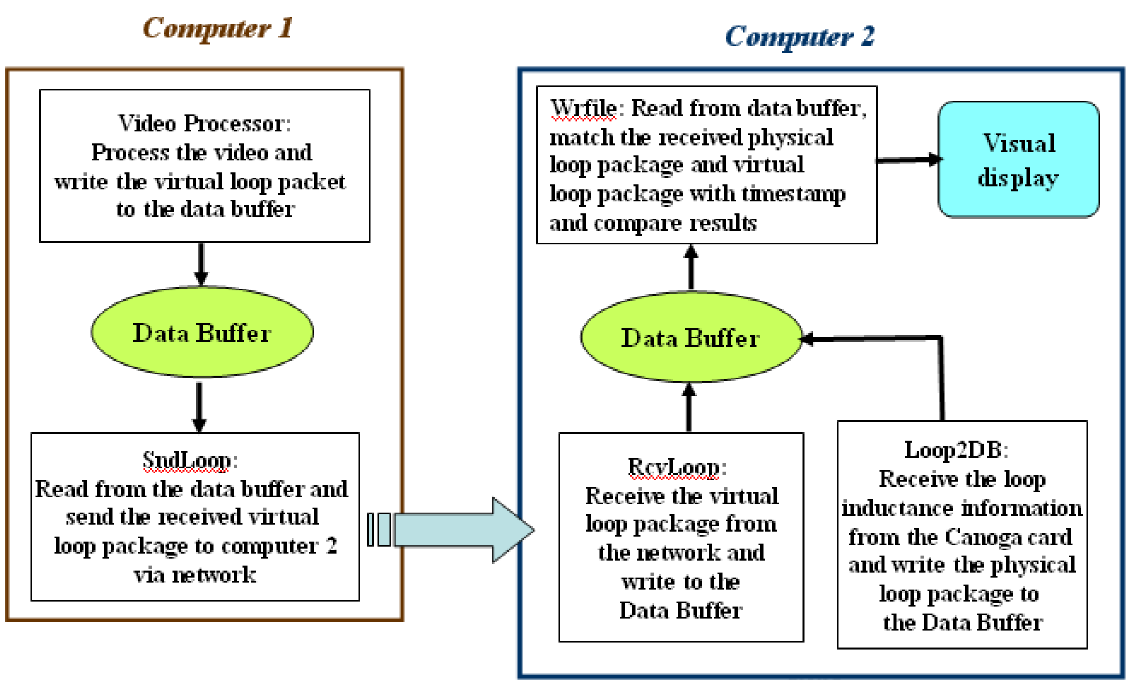


Figure 3.9. Software structure and interaction for the two computer Laptops

3.6 Synchronization of the Two Computers with Wireless Communication

The two data streams (from the loop and the video camera) includes timestamps for matching. Potential faults are diagnosed by comparing the matched data pairs. The video processing data and the loop data are collected with time stamps in two different computers. Therefore, computer system time synchronization is critical.

We use wireless-based (UDP) synchronization tool developed by the California PATH to synchronize the two computers within 1 millisecond difference. The procedure is described as follows:

Step 1: *Computer A* send a signal packet, *MSG1*, to *Computer B* containing its current system time, say *Start_TIME*.

Step 2: When *Computer B* receives the signal packet *MSG1*, it immediately sends back the acknowledge signal packet, *MSG2*, to *Computer A*, which contains:

a) the *Start_TIME* from the packet it received

b) the current system time on *Computer B* at the time of receiving the packet from *Computer A*, say *Rcv_TIME*

Step 3: *Computer A* gets the acknowledge message, *MSG2*, and marks the current system time after receiving *MSG2* from *Computer B*. Then, the round trip time *R1* of data passing is calculated by subtracting the Start_TIME from the current system time. The clock skew between the two computers are then estimated by comparing *Rcv_TIME* with (*Start_TIME*+0.5**R1*).

Step 4: *Computer A* sends a time setting packet to *Computer B* with the clock skew and *Computer B* adjusts its system time accordingly.

The above process is iterated for 100 times and the average round trip time are used to estimate the clock skew. According to our experiment, the resulting clock skew is far less than 1 millisecond. It is a much more accurate and reliable way to synchronize the two computers than other affordable methods, such as using GPS units.

3.7 Comparison of Physical Loop and Virtual Loop

Figure 3.9 illustrates the system structure developed to graphically monitor and compare the loop information. The instantaneous physical loop information and virtual loop information packets are processed and formatted as follows:

```
Loop Information Package
typedef struct{
   double timestamp;
```

```
    double Inductance[Max_Loops];
}Loops_TYPE

Virtual Loop information package
typedef struct {
double timestamp;
double On[Max_Loops];
}Virtual_Loops_TYPE
```

Thus the physical loop packet and virtual loop packet are matched based on the time stamp. However, the packet update rate from the vision system and that for Canoga card are different. The update of information packet for a vehicle over the virtual loop in the vision system is about 10 fps. The maximum update rate from the Canoga card is around 13 Hz. So this is not a one-to-one matching. On the other hand, the messages from both sides could possibly have some delay due to wireless communication or some other unknown reasons. To solve this problem, two Fist-In-First-Out (FIFO) buffers were built on the cabinet computer. One is used to store virtual loop packets from vision system and the other is used to store the physical loop packets from the Canoga card. With those two buffers, two initially synchronized computers can work independently as long as the data is time stamped. Each packet from the video computer (which has a lower update rate) is matched with the physical loop packet which has the closest time stamp by looking up their buffer. This approach significantly increases the reliability of the system.

Currently, the Loop Information Packet includes: time stamp and inductance. Occupancy can be deduced for a given sensitivity threshold. One of the research topics in the near future is to develop an adaptive sensitivity to address the inductance fluctuation caused temperature and humidity over the loop the road surface.

3.8 Preliminary Experimental Data Analysis

Tests have been conducted at the Experimental Intersection in PATH Headquarters, RFS, U. C. Berkeley.

Figure 3.10-3.11 shows the vehicle detection and tracking process. A virtual loop is turned on (as highlighted) when the vehicle ellipse hits the loop rectangle in the world coordinates in the vision system.

We tested the system for around one and half hours at the RFS at UC Berkeley and all of the vehicles passed through the intersection have been detected from both virtual loop system and physical loop system based on the observation. Note that it is a particularly difficult environment for video processing due to heavy moving shadow of trees shaking by a strong wind. The packet buffer described in the previous section makes the synchronization only have an average error of 0.0436 seconds, which means an error of 1.16 meters in space if the vehicle runs at 60 mps. Figure 3.12 - (a-e) shows the comparison of detections from virtual loops and physical loops when the vehicle is running at different speeds. The red bars represent the virtual loops' on/off information and the blue bars indicate the inductance changes of the physical loops. Each column shows a pair of results for the corresponding virtual and physical loop. The reference origin time in the four sub-figures is exactly the same. The x axis represents the time domain with the number of packets as a unit. Since the vision algorithm works at around 10Hz, each packet is about 0.1s long. In our experiment, two loops were monitored. The exact physical loop size was 2 meters in width by 1.8 meters in length. Considering the vehicle's physical length, the efficient length of a regular sedan is around 6 meters.

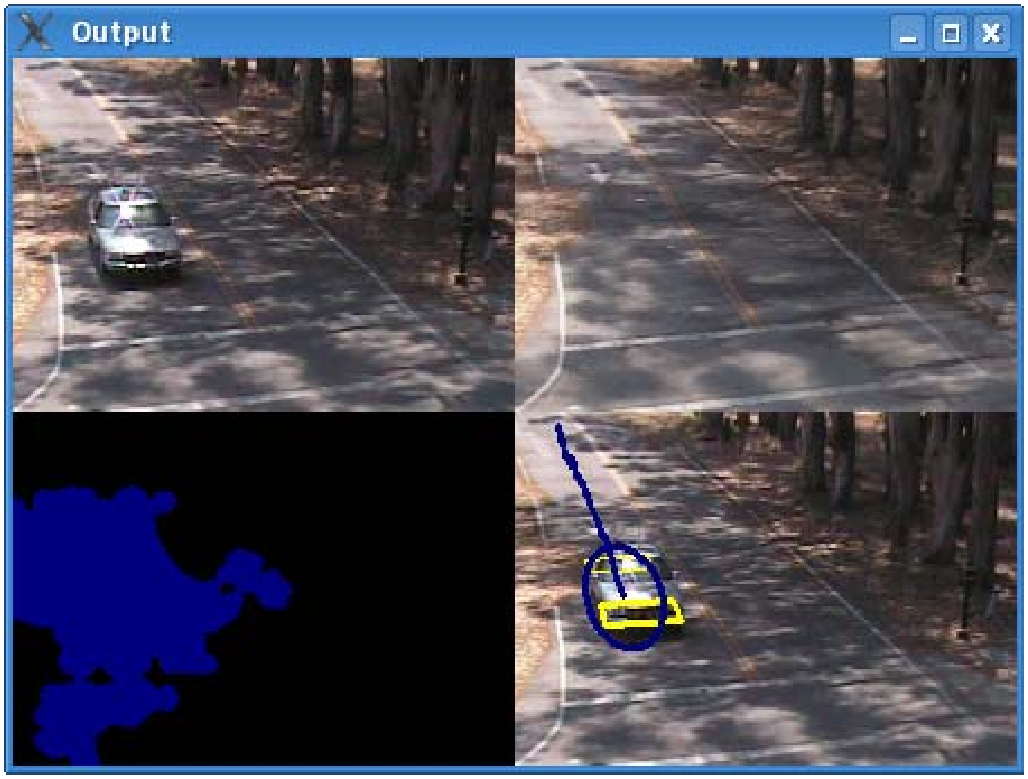
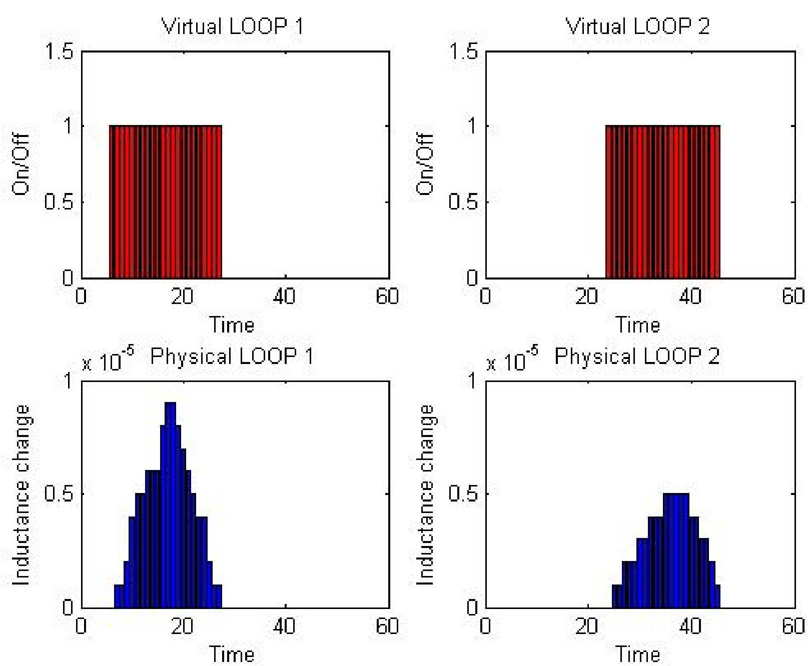


Figure 3.10. Vehicle tracking with virtual loop matched with real loop on the ground

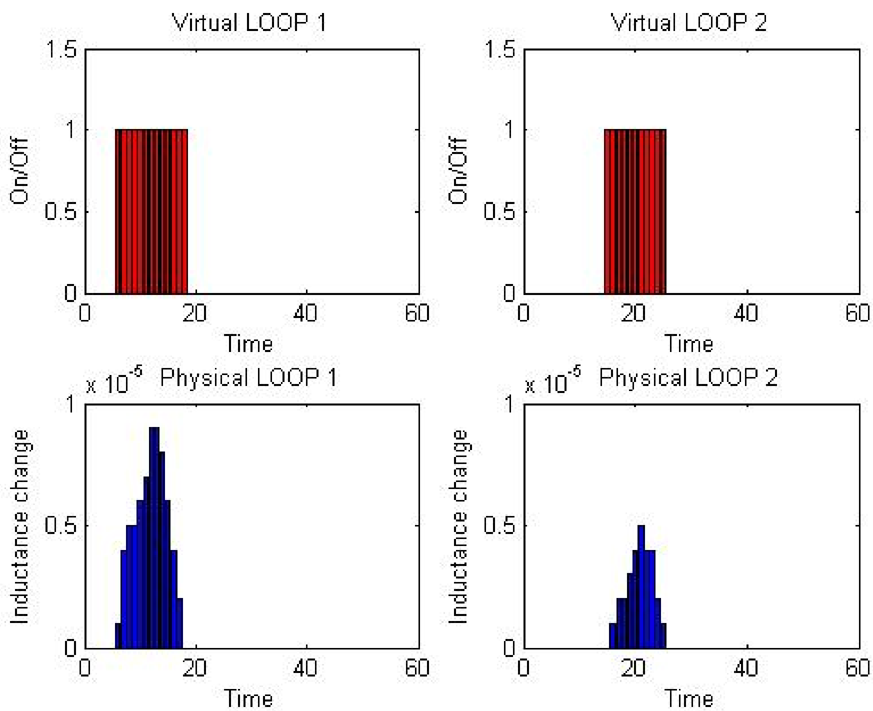
In Figure 3.12, we see that at a low speed, such as 5 mph in (a), 15 mph in (b) and 25 mph in (c), the physical loop data is bell-shaped, while at high speed, such as 45 mph in (d) and 50 mph in (e), it is shown as a signal pulse. The vertical is the inductive intensity variation calculated based on variation of the pulse frequency of the loop as a vehicle passing over relative to the inductance of absence of vehicles. It can be observed that as the vehicle speed increases, the occupancy time decreases. At the speed of 50mph, the duration only lasted for two time steps. Even in higher speed, it is expected that, the vehicle over loop can still be caught due to high frequency pulse signal of the loop circuit. For the vehicle tracking over virtual loop with video, the time instant for virtual loop ON (with a over it) can still be guaranteed due to continuous tracking in advance.

Note that the inductance intensities of the two nearby loops are different even for the same vehicle passing at the same speed. This implies a practical challenge in directly using the inductance data as the only vehicle signature for re-identification over different loops.

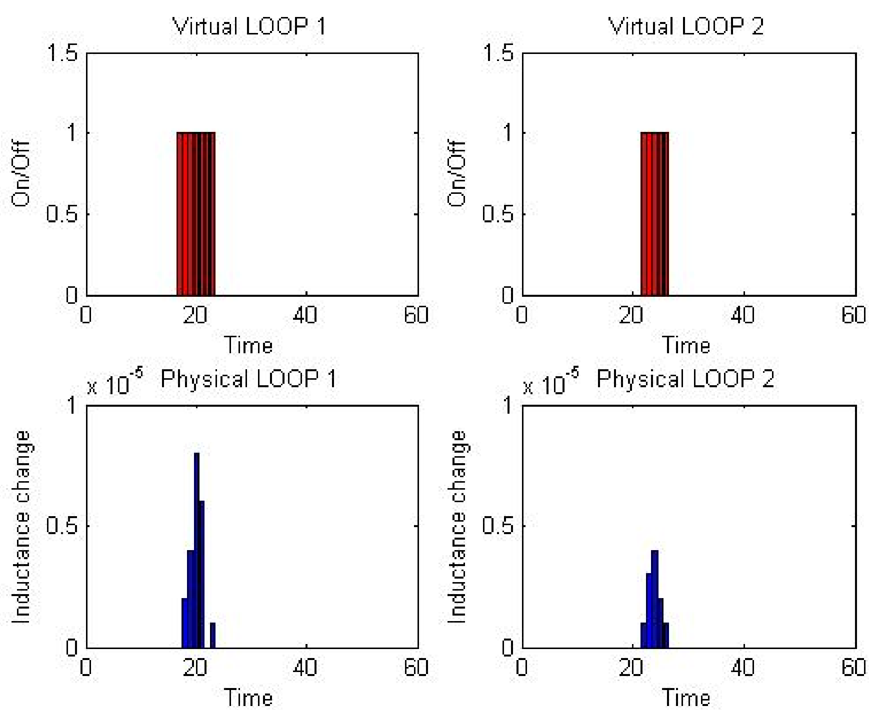
Figure 3.11. Vehicle tracking with virtual loop matched with real loop on the ground



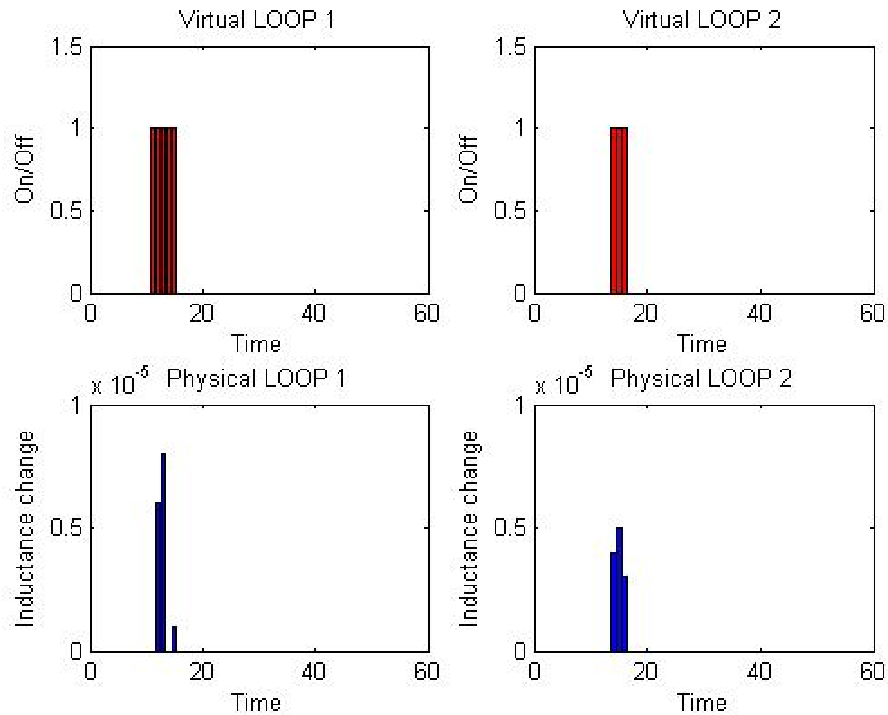
(a) vehicle speed at 5mph



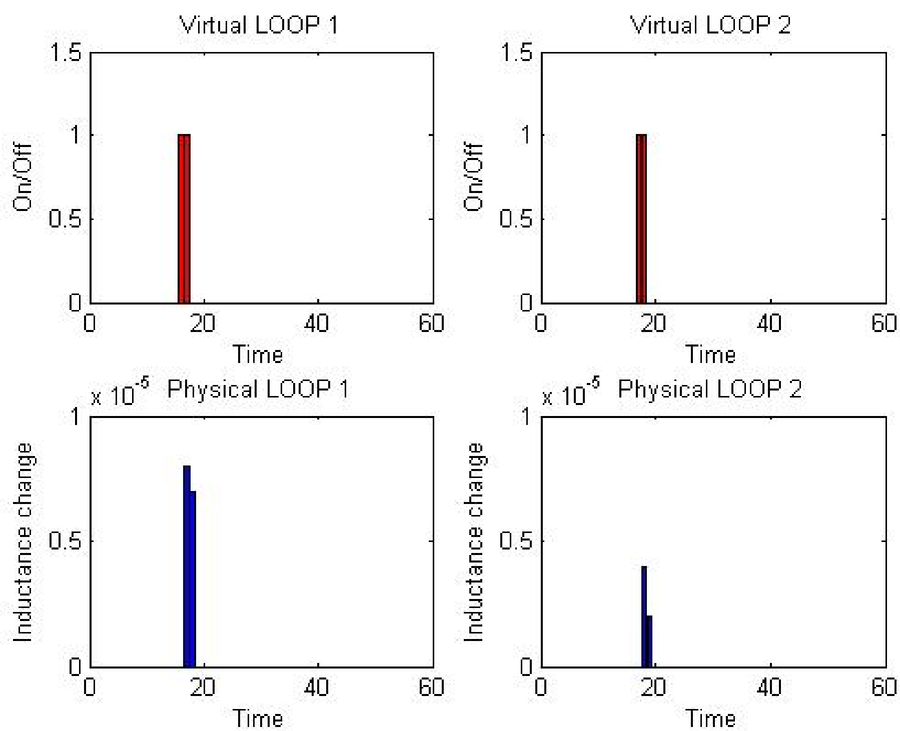
(b) vehicle speed at 15mph



(c) vehicle speed at 25 mph



(d) vehicle speed at 45 mph



(e) vehicle speed at 50mph

Figure 3.12 (a-e) Comparison of the virtual loops and physical loops data when the vehicle is running at different speeds. The time duration of the signal in each plot is the duration of the vehicle practically over the loop.

3.9 Loop Sensitivity with Respect to Several Factors

It was believed that traffic data, basically the occupancy, from inductive loop is affected by the sensitivity of the loop card set. For Reno 222 loop detector card, such sensitivity level is usually set manually which means that traffic engineers have to go the field to adjust it if the corresponding loop data reading seems incorrect. Surely, this may not fix the problem since sensitivity is only one of many possible causes to the bad data reading. It was believed that the sensitivity of the loop card may be affected by several factors: the installation of the loop circuit, road surface temperature, road surface humidity, vehicle types (basically the height of the axles and locations), vehicle speed over the loop circuit. To investigate if those factors really affect sensitivity, if it does, to find out how it affects, we designed some test scenarios and tested using the loop and control cabinet facility at Research Intersection of PATH at Richmond Field Station.

Tests were conducted to analyze the sensitivity of the inductive loops and the 3M Canoga Card:

- Four vehicle types were used for the tests including:
    - full size passenger car
    - SUV
    - full size van
    - the tractor of Class-8 commercial heavy-duty truck
- each vehicle type was run when the road surface over the inductive loop was dry and wet (splashed with water while vehicles is running) respectively
- each combination above have been run at different speeds from 10mph to 40mph with increment of 5mph
- each run was conducted in two opposite directions over the loop

Detailed test scenarios were listed in the Table in the appendix.

Preliminary analysis showed that, except the vehicle speed affects the occupancy of the loop signal, both vehicle types and humidity would not affect the magnitude and shape of the inductive signal significantly. This may be due to the internally built-in capability of adaptive sensitivity adjustment of the 3M Canoga card.

3.10 Concluding Remarks and Further Work in this Direction

We presented the research and development of a portable tool for systematic loop fault detection at the control cabinet level. Experimental tests up to 50mph of a vehicle speed demonstrated that this concept is feasible in operating in real-time. Continuous tracking of the vehicles from further the upstream of the loop guaranteed that the vehicle is reliably caught over a loop even at a high speed. An effective and reliable synchronization and data communication scheme was presented. Experimental results showed that the matching of the two sensors were reliable -- it had never missed for over 30 tests.

The next step of the research will be in three directions: (a) testing on real freeway (such as the Berkeley Highway Lab test-bed) and interfacing with the 170 controller for practical deployment; (b) testing and improving for multi-lane and multi-vehicle tracking algorithm; and (c) developing algorithm for systematic loop fault detection, data correction, and cleansing at the control cabinet level.

Future work in this part include: to show you can match a sequence of bivalent data from vehicle tracking based video camera and the loop bivalent data, say cars and trucks continuously across different speeds. This can be done with two methods: (a) to test at PATH intersection with different types of vehicles with known speeds; (b) to conduct field on freeway for different traffic situations with density: low, medium, and high. Vehicle types of the latter can be identified either automatically which may need further software development, or manually by playing back the video clips. This would require the vehicle tracking algorithm to be (i) reliable detection and tracking of multiple lane vehicles; (ii) vehicle classification based on length detection.

Chapter 4 Systematic Loop Fault Detection and Data Correction Strategy

The purpose for developing PLFDT is for systematic loop fault detection and providing high quality even (low level) data. This chapter presents a list of strategies for such purpose. To guarantee high quality even, the data system need to have the following functions:

- automatically detection and report some higher level problem such as communication and power outages;
- automatically detection, isolate and report the type of the data error and its possible causes;
- automatically isolate the problem from high level (TMC/PeMS) to low level (Controller cabinet) by allocating suspicious loops and corresponding Controller cabinet;
- automatically recommend the method for problem fixing such as field visit for further detection using PLFDT or some hardware fixing method;
- using developed algorithm and software to avoid/prevent even data quality drop caused by some intermittent problems due to odd driver behaviors and instability of loop detector cards (quality and sensitivity).

The enclosed table (Table 4.1) is just a preliminary thoughts and it is not exhaustive. The table will be refined and improved gradually. More loop system faults, their detection strategies and algorithm and software to prevent even data quality drop will be added to it with further development of the project.

Although, those strategies are developed for inductive loop detectors, some are applicable to other traffic detectors.

Table 4.1 Systematic Loop Fault Detection Strategy

PLFDT - Portable Loop Fault Detection Tool: prototype has been developed at California PATH by the research team, which can used for real-time detection or offline data analysis if corresponding data are available. In fact, most loop fault can be detected through offline data analysis.

Fault Type (Symptom)	**Possible Causes and Detection Methods**	**Recommended Treatment**	
		Algorithm and Software for Error Prevention and Data Correction	**Problem Fix from Hardware**
• No/Insufficient data in a region or freeway section •	Communication error Line, Packet loss, UPD, TCP Detection: TMC/PeMS level aggregated data analysis to investigate: (a) communication problem; (b) to locate suspicious controller cabinet If communication error is excluded, field visit and investigate using PLFDT at control cabinet;	Automatic communication error detection – adding real-time counting is data packet; Event data quality checking for occupancy and flow;	
Synchronized error • District • Freeway corridor • A section of freeway	Communication or power outage Detection: TMC/PeMS level aggregated data analysis to investigate: (a) communication problem; (b) power system failure; If communication error is excluded, field visit and investigate using PLFDT at control cabinet;	Automatic communication error detection – adding real-time counting is data packet; Event data quality checking for occupancy and flow;	

Inconsistent speed/ occupancies for adjacent lanes persistently even in night hours	Card quality or Different types of card working in the same environment Detection: locate suspicious loops and controller cabinet for field visit and investigate using PLFDT;	Algorithm and software for data correction taking into account time of day traffic characteristics; Event data quality checking for occupancy and flow;	Change to high quality card Change to the sane cards
No data from some individual loops	Open loop/circuit, wiring, power; missing parts; Disconnected by road service; Detection: locate suspicious loops and field visit to detect at control cabinet using PLFDT: to compare loop data with video data;	After connection, even data quality checking for occupancy and flow;	Hardware maintenance is necessary;
Insufficient data from certain loops	Communication problem; Loop detector problem; Card sensitivity problem; Detection: TMC/PeMS level aggregated data analysis to locate suspicious loops and to exclude communication error; Using PLFDT at controller cabinet level to exclude card sensitivity/error/quality problem;	Automatic communication error detection – adding real-time counting is data packet; Event data quality checking for occupancy and flow;	
Mis-assignment in (a) highway direction; (b) between lanes; (c) upstream and downstream or a dual loop	Internal loop map use in loop card data decoding; Wiring Detection: TMC/PeMS level aggregated data analysis to locate suspicious loops and cabinet; Field visit using PLFDT: persistent check of flow from loops in adjacent lanes;	Switching lane number assignment in data reading and logging; Event data quality checking for occupancy and flow;	Changing wiring connection for permanent fix;

Mis-assignment in (a) highway direction; (b) between lanes; (c) upstream and downstream or a dual loop	Internal loop map use in loop card data decoding; Wiring Detection: TMC/PeMS level aggregated data analysis to locate suspicious loops and cabinet; Field visit using PLFDT: persistent check of flow from loops in adjacent lanes;	Switching lane number assignment in data reading and logging; Event data quality checking for occupancy and flow;	Changing wiring connection for permanent fix;
Cross-talk	Sensitivity; Interference between loop detector cards; Detection at control cabinet using PLFDT: Compare neighbor loop signals	Algorithm to prevent effects on data; Event data quality checking for occupancy and flow;	Swapping detector card; Change to smart cards; Use the same card in a controller cabinet;
Pulse flickering, Chattering, Miss firing	Loop cards were in “pulse” mode, “pulse” mode is not appropriate for freeway detectors; Loop circuit connecting problem; Cad quality problem; Hardware for generating signals; Detection: Field visit or offline data analysis using PLFDT for adequate long period of time;	Software prevention: Control cabinet filtering using low pass filter; prediction and duration bound checking; interpolation and extrapolation to smooth up; Event data quality checking for occupancy and flow;	
In consistent data quality problem from time to time, and form lane to lane without communication problem	Card sensitivity Card quality Detection: at Controller cabinet level use PLFDT; or through offline data analysis;	Smart card has solved the sensitivity problem already; Algorithm and software to prevent data quality drop through prediction/correction/imputation; Event data quality checking for occupancy and flow;	Change to smart card Using the same type of detector cards in a controller cabinet;

Mismatch between upstream & downstream loops signal for dual loop stations	(a) Transition (b) Vehicle lane changing (c) Card signal reliability (d) Other card quality issue (e) Installation difference Detection at control cabinet using PLFDT to exclude the possible of such mismatch from software (data reading and logging) problem	Real-time algorithm for data correction/prediction/imputation; Event data quality checking for occupancy and flow;	Change to smart card to exclude card quality/sensitivity problem; Using the same detector cards in the controller cabinet;
Persistent occupancy duration and flow problem: • Occupancy and flow are mostly zero • Very high occupancy • Constant occupancy and flow	*If temporarily:* Large vehicle tracking Heavy Traffic/incident cause stop *If persistently:* Loop card sensitivity Detection at control cabinet using PLFDT to investigate: (a) software (data reading and logging) problem; (b) card quality problem; (c) problem of pulse signal directly from the loop circuit;	Event data quality checking for occupancy and flow;	Change to smart card to exclude card quality/sensitivity problem; Using the same detector cards in the controller cabinet;

Recommended Activities:

To use the same type of detector cards in the same Controller cabinet;
To use smart card if possible;
To add counting in data packet for automatic detecting and warn of communication error; to calculate communication failure for each detectors and quality assessment;
To properly install loop detector system;
To add software for even data quality checking at Controller cabinet level and report the data quality to TMC/PeMS regularly.

Chapter 5 Data Cleansing and Correction in Microscopic Level

This chapter describes some method used for data cleansing, imputation and correction at microscopic level automatically. Those faults could be intermittent faults such as cross-talk, or permanent faults such as mis-assignment. It can be used for data error caused by some loop faults without incurring traffic engineers to access the traffic controller.

5.1 Future Data System Hierarchical Structure

Also some data processing algorithms that could be used in control cabinet micro-level or higher level for the application of loop data for traffic state parameter estimation are presented. The example of local application of loop data is for local ramp metering control or intersection traffic light control. The higher level data processing application include the Coordinated Ramp Metering and Variable Speed Limit control of freeway traffic along a highway corridor, which may be further coordinated with the arterial traffic control. In this case, the loop detector data may be used locally as well semi-globally as in TMC (Traffic Management Center). This hierarchical structure for data collection, sensor fault detection and data processing is shown in Figure 5.1.

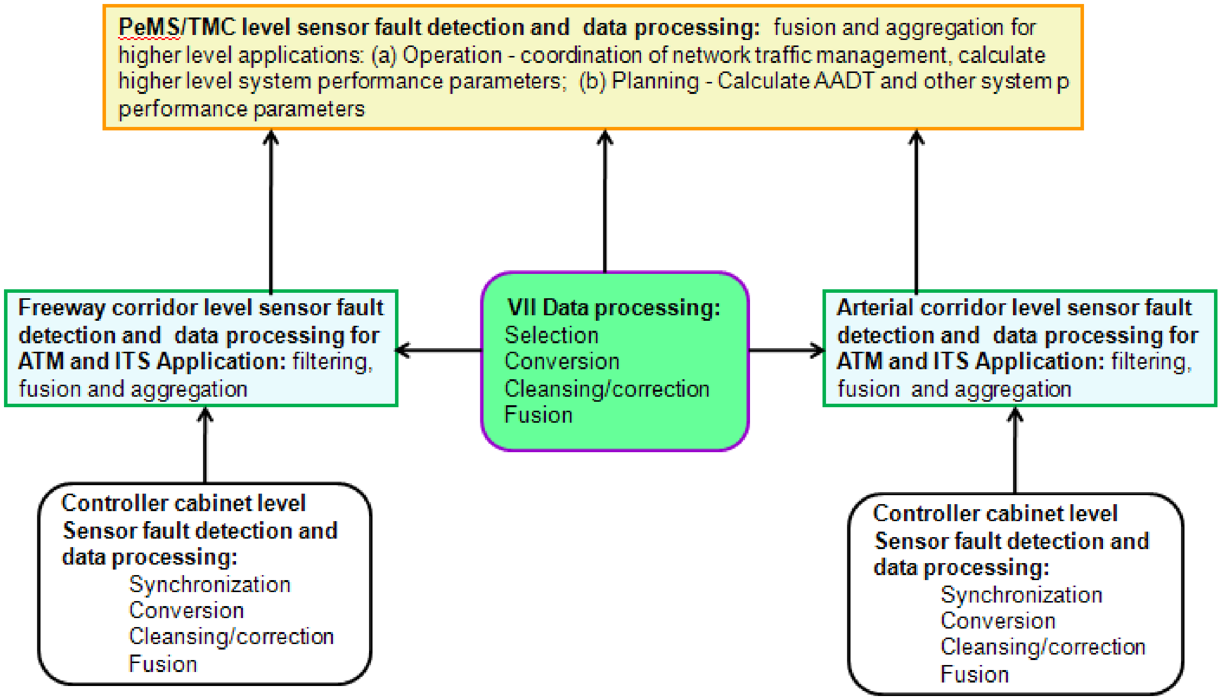


Figure 5.1. Expected Future Data System Structure

5.2 Traffic State Parameter Estimation Error

Dual loop station make it possible to estimate vehicle speed using loop on/off time instant based on sub-second loop data [7]. However, noise still exists. An experimental study conducted by Chan and May [1] showed with field data that the average detector pulse on-times for two longitudinally closely spaced stations could vary by 5~10%, or even higher. This implies that care still needs to be taken for using dual loop sub-second data for traffic parameter estimation. Besides, techniques developed in FSP and PeMS for data correction and cleansing as pre-processing[22, 23, 27], and other linear filtering are used to smooth the data in this work.

General estimation error includes two types: absolute error and time delay. As is known, for speed estimation, time delay also makes contribution to absolute estimation error. This is particularly true if there is speed fluctuation which happens very often for congested traffic.

Traffic flow may be divided into four phases: free flow, congestion on-set, congested static state, recovering (from congested to free flow). Since the mean speed trajectory has different characteristics for each phase, the estimation error will behave differently. For free-flow and congested steady state which are homogeneous flow, there is not much speed fluctuations. Thus time delay in the estimation does not play significant role to the error except in the first transient period. For congestion onset and recovering phases, the traffic flow has negative and positive acceleration respectively. Time delay in the estimation makes a significant contribution to estimation error. Intuitively, if one shift a non-constant signal by a time interval $\Delta T > 0$ and then compare it with the original signal, the vertical difference – the error would become apparent. This is the reason to reduce time delay to improve traffic parameter estimation.

5.3 Time Delay and its Effect on Traffic Parameter Estimation Error

Work in [7] considered traffic parameter estimation error based on loop station at fixed point. Beside sensitivity, several other important factors have been identified that would affect the estimation error: sensor measurement error, estimation method, and time delays. Detailed discussions are referred to [16].

In traditional traffic management and planning, data aggregated over time and distance were common practice. To see this more clearly, it is necessary to separate real-time data processing and archived data off-line processing since the data availability and methods used in the two situations are quite different. For example, for real-time processing, data available at time instant t are at most all the data in the past up to current, but not the future data; however, for archived data, one can use data later than current instant t for processing. This is the reason why after-processing archived data can produce much better results than real-time data.

Time Delay Caused Aggregation Method

Let's look at the time delay caused by Moving Window Averaging popularly used in real-time data aggregation. Now if one wish to aggregate every N time intervals Δt, the sampling time interval. The data of the last N time steps with o, the occupancy, to be to be estimated. Suppose the method for aggregation is simply averaging:

$$\bar{o} = \frac{1}{N}\sum_{i=1}^{N} o\left(t-(i-1)\Delta t\right)$$

From formal Taylor expansion:

$$\begin{aligned}
\bar{o} &\sim \frac{1}{N}\sum_{i=1}^{N}\left(o(t)-\dot{o}(t)(i-1)\Delta t\right) \\
&= \left[\frac{1}{N}\sum_{i=1}^{N} o(t)\right]-\left[\frac{\dot{o}(t)\cdot\Delta t}{N}\sum_{i=1}^{N}(i-1)\right] \\
&= o(t)-\frac{N^2}{2}\frac{\dot{o}(t)\cdot\Delta t}{N} = o(t)-\frac{N\cdot\Delta t}{2}\dot{o}(t)
\end{aligned} \tag{3.1}$$

which means the time delay caused by this moving window average in the level of $\frac{N\cdot\Delta t}{2}$.

Estimation Error Caused by Time Delay

If a traffic parameter is a constant or near constant value such as free-flow speed, time delay does not matter much. However, when the traffic parameter varies significantly over time, the error caused by time delay would be more significant as seen from (3.1) that

$$\left|\bar{o}-o(t)\right| \sim \left|\frac{N\cdot\Delta t}{2}\dot{o}(t)\right|$$

which depends on the slope of occupancy $\left|\dot{o}(t)\right|$.

More Attention Needed on Time Delay Needed for ITS Application

The effect of time delay in traditional traffic data analysis was not well-recognized due to several reasons:

- Sensor detection system was not developed in 15 years ago: compared to sensor systems 15 years ago when single loop detection system and probe vehicles were the main tools for traffic data collection; nowadays, dual loop station, video camera, microwave/laser/infrared radar systems, cell-phone with GPS, Weigh-in-Motion system, sensor network with wireless capabilities such as Sensys Systems are all commercially available for traffic monitoring and detection; those commercially products can provide traffic data from many point of view.

- Communication system for synchronized data passing was not generally available; today GPS equipment has been widely used. Its UTC time is generally used as data time stamp, which could be used for real-time processing or in archived data for after processing;
- Most importantly, traffic management and control needs: with the development of ITS technologies, traffic management has also developed from planning into real-time operation such as traffic signal control and optimization, incident detection and handling, freeway ramp metering, and traffic speed regulation, of which congestion onset is only one important piece of it. The development also brings new challenges to traffic monitoring and detection. One of the most important change for traffic monitoring and detection is to provide more accurate estimation of traffic parameters in real-time with delay or hysteresis.

5.4 Data Filtering with Low Pass Linear Filter

Now Caltrans Districts have mandated that all the loops to be installed in the future are to be dual loop station. It is well-known that dual loop station provide good point estimation of the fundamental traffic state parameters such as speed, flow and occupancy. Other traffic parameters such as density and link travel time necessary for traffic control and ATMS can be inferred from those fundamental traffic parameters. Therefore, this project uses the features of dual loop station for lower level data cleansing, correction and imputation. Those data error may be due to different causes and could be intermittent such as cross-talk or persistent such as mis-assignment. The recorded Berkeley Highway Lab (BHL) raw loop data from 170E control cabinet are decoded to give each station (as shown in Figure 3.12) ON and OFF time instant counted as the number of (1/60)s. Thus the information obtained is practically 60Hz. The raw data need to be cleaned, properly matched for upstream-downstream of the same station, and missing data to be imputed. Then speed and occupancy estimation for each lane at each dual loop station are estimated using the method similar to those introduced in [7]. The following 2nd order low pass real-time Butterworth filter is used afterwards to smooth up the occupancy and the speed trajectories with respect to time at each station.

$$
\begin{aligned}
& x(t+1) = A \cdot x(t) + B \cdot x_{in}(t+1) \\
& y_{out}(t+1) = C \cdot x(t) + D \cdot x_{in}(t+1) \\
& t = 0,1,2,\ldots \\
& \text{A}=\begin{bmatrix} 0.2779 & -0.4152 \\ 0.4152 & 0.8651 \end{bmatrix}, \text{B}=\begin{bmatrix} 0.5872 \\ 0.1908 \end{bmatrix} \\
& \text{C}=[0.1468 \quad 0.6594], \quad \text{D}=[0.0675] \\
& x(0) = x_{in}(0)
\end{aligned} \tag{3-1}
$$

where $x(t) = \left[x_1(t), x_2(t)\right]^T$ is the filter state; $x_{in}(t)$ is the input signal; and $y_{out}(t)$ is the filtered output single. Through phase analysis, it can be seen that this filter causes time delay less than 0.5s which can be ignored for traffic control purposes. It is noted that the data are not aggregated over time, nor aggregated over distance. However, it is implicitly assumed that if there is no vehicle passing the given station, the speed will keep to be the value of the previous time step instead of setting it to zero. The purpose to do so is to avoid unnecessary speed fluctuations. It is important to note that the filter here can be used for real-time data processing for all types of traffic state parameters estimations such as occupancy, density, speed, flow and travel time.

5.5 Speed Estimation Based on Dual Loop Station Data

As a typical example, the following analysis shows that raw data update rate from a dual-loop station may be required as fast as possible for more precise estimation of vehicle speed as required by traffic control and management purposes. It is supposed that the speed estimation is based on the ON/OFF time instants when the vehicle is over the upstream loop edge and downstream edge and the inter-loop distance, which is generally used for dual loop stations.

$d_u = 6.1m$ – distance between upstream edges (or downstream edges) of dual loops,

T_{on}^u – upstream edge on time instant

T_{off}^u – upstream edge off time instant

T_{on}^{d} – downstream edge on time instant

T_{off}^{d} – downstream edge off time instant

v_{est} – estimated vehicle speed

Then vehicle speed can be estimated as:

$$v_{est} = \frac{1}{2}\left(\frac{d_u}{\left(T_{on}^{u} - T_{off}^{u}\right) + \Delta^u} + \frac{d_d}{\left(T_{on}^{d} - T_{off}^{d}\right) + \Delta^d}\right)$$
$$= \frac{1}{2}\left(\frac{6.1}{\left(T_{on}^{u} - T_{off}^{u}\right) + \Delta^u} + \frac{6.1}{\left(T_{on}^{d} - T_{off}^{d}\right) + \Delta^d}\right)$$

$\Delta^u -$ uncertainty of upstream time instant difference

$\Delta^d -$ uncertainty of downstream time instant difference

Or simply using:

$$v_{est} = \frac{6.1}{\left(T_{on}^{u} - T_{off}^{u}\right) + \Delta^u}$$
$$= \frac{6.1}{6.1/v_{real} + \Delta^u}$$
$$= \frac{6.1 \cdot v_{real}}{6.1 + \Delta^u \cdot v_{real}}$$

where $v_{real} -$ is the real vehicle speed. This is reasonable since the same delay is likely to happen to the downstream on-off time difference.

As an example, if the time delay is 0.1s. Then the uncertainty magnitude would be in the following range:

$$0 \le \Delta^u < 0.1s$$

If the worst case is considered, then the estimated speed v_{est} would become:

$$v_{est} = \frac{6.1 \cdot v_{real}}{6.1 + 0.1 \cdot v_{real}}$$

As such, when real vehicle speed is at *35m/s*, the error generated by the time delay is:

$$v_{est} = \frac{6.1 \cdot v_{real}}{6.1 + 0.1 \cdot v_{real}} = 22.2396$$

So the maximum error is: $v_{err} = 12.6\text{m/s}$ which is *36.5%*. If update interval is 0.5s that's *500ms*, then $v_{est} = 9.046 m/s$ and $v_{err} = 25.9534 m/s$ which is *74%*. Those arguments indicate how time delay in data passing is important, which determines the requirement for loop data update rate.

Similar method applies to the estimation of occupancy.

5.6 Data Correction to Mismatch of Upstream and Downstream Data

To use the method above, a critical requirement is that the ON-Time and OFF-Time instants of upstream loop and downstream loop should be matched into pairs. Even if the two loops are connected with the same loop detector card, such a match is not necessarily guaranteed. It is thus necessary to have pre-process with fill up those gaps. Otherwise, significant noise/error will be generated in the estimation of point speed and occupancy. For this purpose, the following method has been developed. It is noted that although this method has been used for off-line data analysis, it applies to online data as well.

Since the dual loop stations is mandatory for installation in Caltrans, and dual loop provide much better traffic state parameter estimation such as speed, flow and occupancy, it would make better sense to focus on the lower level data correct of dual loop stations. Petty first considered the low level data problem for dual loop stations in [24]. The first problem is the mismatch between upstream and downstream ON/OFF time instant, which the author call them "Transition times". This problem is shown in the following

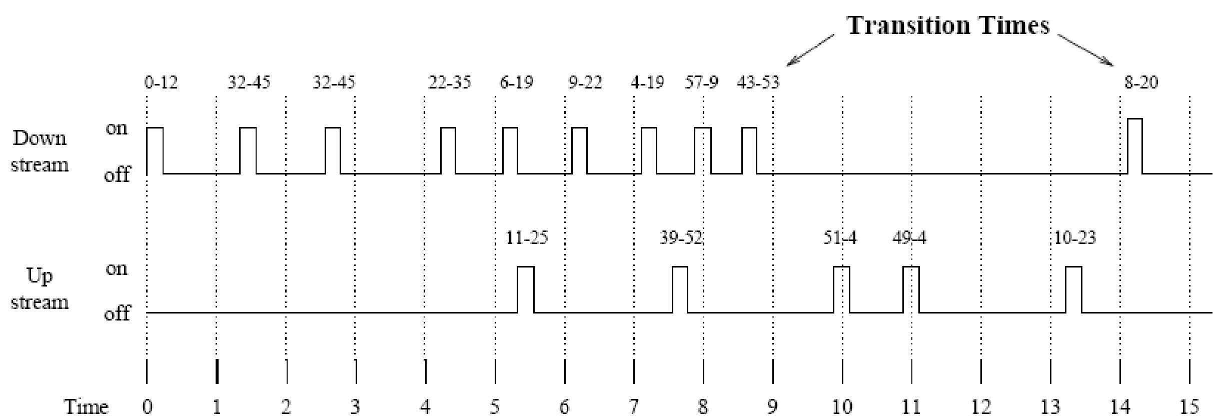


Figure 5.2 Mismatch between upstream and downstream ON/OFF time instant

In Figure 5.2, the controller clock time is divided in second separated with dotted lines and numbered in the lower row. The upstream and downstream ON/OFF time duration are shown with bars. It is obvious that with such mismatch, it would be very noise using the ON/OFF time saint of the dual loop for speed estimation.

As discussed before, some data correction method proposed in [22] for vehicle count, point speed, and occupancy are from macroscopic viewpoint and for post-processing instead of real-time. The algorithm presented here can be used for real-time processing since it only use the information up to current time point.

Algorithm development for effective correction of such mismatch problem is underway.

5.7 Algorithm for Data Synchronization and Aggregation

For traffic modeling and control purposes, averaging (aggregation) the speed trajectories across all lanes at a station is necessary sometimes. For example, in the incident detection and Variable Speed Limit control of main lane traffic, it is necessary to have accurate estimation of traffic speed at the location of sensors, which require as less time delay as possible. The algorithm presented below is for such purposes. However, if one satisfies with high level aggregated data over time, the algorithm here is not very helpful unless the high level aggregated data still have some data pissing over time for some lanes.

Data aggregation across lanes for lower level data on the freeway is not straightforward since a vehicle arrival triggers a loop station ON is at random time instants for different lanes. Those time instants for each lane at the same station are independent. Alternatively, the discrete time points for the dual loop in each lane of the same station are NOT synchronized. To overcome this difficulty, a common time interval $\Delta t = 1.0s$ is selected and the following interpolation methods are used for synchronizing all the 5 lane data as follows: Suppose $\left\{t_0^{(i)}, t_1^{(i)}, t_2^{(i)}, ..., t_{N_i}^{(i)}\right\}$ is the time points for the discrete speed and occupancy trajectories for Lane i of the given station. Set $N = \min\left\{N_1, N_2, N_3, N_4, N_5\right\}$ and generate a common time sequence $\left\{t_0, t_1, ..., t_N\right\}$ as: $t_0 = 0, t_n = n \cdot \Delta t,\ n = 1, ..., N.$ Now for each lane i, synchronized speed trajectory $\left\{v^{(i)}(t_0), v^{(i)}(t_1), ..., v^{(i)}(t_N)\right\}$ and occupancy trajectory $\left\{o^{(i)}(t_0), o^{(i)}(t_1), ..., o^{(i)}(t_N)\right\}$ are constructed through linear interpolation as follows: if $t_j^{(i)} \le t_k \le t_{j+1}^{(i)}$, then

$$
\begin{aligned}
v^{(i)}(t_k) &= v^{(i)}\left(t_j^{(i)}\right) \cdot \frac{t_{j+1}^{(i)} - t_k}{t_{j+1}^{(i)} - t_j^{(i)}} + v^{(i)}\left(t_{j+1}^{(i)}\right) \cdot \frac{t_k - t_j^{(i)}}{t_{j+1}^{(i)} - t_j^{(i)}} \\
o^{(i)}(t_k) &= o^{(i)}\left(t_j^{(i)}\right) \cdot \frac{t_{j+1}^{(i)} - t_k}{t_{j+1}^{(i)} - t_j^{(i)}} + o^{(i)}\left(t_{j+1}^{(i)}\right) \cdot \frac{t_k - t_j^{(i)}}{t_{j+1}^{(i)} - t_j^{(i)}}
\end{aligned}
\tag{4-9}
$$

Then the mean value of the synchronized trajectories for all the lanes at a given station can be simply calculated at the synchronized time points t_k as follows:

$$
\begin{aligned}
\bar{v}(t_k) &= \frac{1}{N} \sum_{i=1}^{N} v^{(i)}(t_k) \\
\bar{o}(t_k) &= \frac{1}{N} \sum_{i=1}^{N} o^{(i)}(t_k)
\end{aligned}
\tag{4-10}
$$

where N is the number of lanes.

Chapter 6 Communication System Consideration

Different sensor data would have different uses. It is necessary to develop an optimal strategy which can satisfy the data needs of traffic management and control and minimize the cost for data passing.

- If passing processed data, how to process at control cabinet?
- If passing reduced raw data, how to reduce data size such that it still keep the original functionality for traffic parameter estimation?
- How to combine the data processing with communication system structure?
- Other related issues.

Loop detector data are usually used in different locations where they were collected. The main uses of traffic data include traffic operation and planning which are integrated in Active Traffic Management alone a corridor, which include

- Demand Management
- Lane (Capacity) Management
    - Lane changing assistance
- Traffic Management
    - Coordinated Ramp metering and Merging Assistance
    - Variable Speed Limit (VSL)

Communication system is indispensible for corridor-wide and/or area-wide data collection, synchronization and integration. However, data loss is very common as passing through communication systems. Communication systems are thus critical to pass the data. Data quality to the end user main depends on the following factors:

- Sensor detection error
- The way the data are pre-processed and packed for sending through communication system
- Reliability of the communication system

There is usually a trade-off between the communication reliability and cost.

Since Phase 1 and 2 of the project were focused on the development of a Portable Loop Fault Detection Tool, communication problem is only preliminarily considered. This chapter presents some work done in this area. Details study and recommendation will be conducted in the next phase of the project. Also, with the research and development of VII (Vehicle-Infrastructure-Integration), which in general sense, will include DSRC (Dedicated Short Range Communication) and Cell Phone, the data collection, processing, passing, storage and use will be affected greatly. We will discuss such impact briefly in this chapter.

6.1 Sensor Data Passing with Communication Systems

Since traffic data passing is required for all sensors instead of just inductive loop detectors, they all will need communication system. The following discussion will apply to all the sensors with which the data need to be passed.

Traffic raw data include those from sensors such as

- inductive loops
- video camera
- Sensys sensor
- radar/lidar
- WIM (Weigh in Motion) system
- Other sensors

Those raw data are massive and thus data size directly related to the bandwidth of the communication system, either wireless or cable. High bandwidth cost much more and they tend to be more unreliable as complained by Caltrans engineers. If we can reduce the size of the data significantly, Caltrans district TMC will be able to able to achieve the same goal for traffic management, control and traveler’s information with much less cost. The discussion in Section 2 shows that the traffic parameter estimation is very sensitive to update rate, which indicate that it is necessary to come up with an optimal strategy for Caltrans district to collect and use the traffic data.

6.2 Current Situations of Communication Systems

We have investigated 3 Caltrans Districts: D4, D7 and D12 regarding the current situation of the available communication system.

Our approach is to look at the PeMS data and use data analysis method to identify possible data loss caused by communication system. To achieve this, we will need detailed information for communication systems between each loop station to TMC in your District. It would be much appreciated if you could provide us a list all the loop station number used in PeMS system under one of the following communication system:

- Fiber optics
- Cell phone
- Old telephone line
- GPRS Modem
- CDPD Modem
- Other media (please specify the name)

It is also important for us to know what is the communication protocol: TCP or UDP. The difference between the two:

TCP: send the packet, the other end receive and acknowledgments. If not received, it may resend to guarantee data reliability.

UDP: It does not use acknowledgments. It sends the packets without waiting on confirmation of received packet. Thus there is no resend even if data got lost.

6.2.1 Caltrans District 4:

Mr. Ray Duschane (Tel: 510-286 5105; Email: Ray_Duschane@dot.ca.gov) is responsible for all the wireless communication systems for data passing in Caltrans D4. According to the discussion with Ray on March 27rg 2007, all the loop data are on wireless. All the CCTV data passing with telephone line or fiber optics are independent from the communication system used for loop data. GPRS modem previously using dynamic IP address. It was then changed to Persistent IP, which is something between static IP and dynamic IP. The disadvantage of dynamic IP is that if there is problem, it may be necessary to take the modem back to TMC for manually rebooting.

From another discussion later on, all of the mainline inductive loop detectors here in the District 4 provided traffic data to Traffic Management Center (TMC) through wireless GPRS communications. In the field, these GPRS modems resided in cabinets along the side of the freeways. The loop detectors for a given location terminated in these cabinets. The traffic engineers identifid each cabinet through a numbering system that begins with the letter DT or E (for example DT864 or E37CM). In PeMs, the cabinet numbers are referred to as MS ID's.

Now each cabinet would normally have one or two sets of mainline loop detectors depending upon whether the cabinet is monitoring one side of the freeway (for example, North or South) or both sides of the freeway (for example, East and West). One side of a freeway was referred as a station. In PeMs, these stations were referred to as VDS ID's. So an MS ID (cabinet) could have one or two VDS ID's (stations) associated with it in District 4.

Unfortunately, the traffic engineers did not know how to extract a list of District 04 MS ID's with associated VDS ID's from PeMs. Also as mentioned previously, for whatever reasons, the MS ID's in PeMs were not all populated with District 4 cabinet numbers. In other words, a lot of times one would find locations with VDS ID's, but the MS ID for that location would be blank. It was suggested to use PeMs to search for District 4 detector stations by routes or counties or etc., and PeMs would provide with all the detector locations for given route or county, etc..

6.2.2 Caltrans District 7

The person responsible for the communication between 170 Cabinet and TMC in Caltrans District 7 was Mr. Alebachew Bekele (Tel: 323 259 1803; Email: Alebachew_Bekele@dot.ca.gov)

Based on the discussion with Mr. Bekele on March 27, 2007, 40% ~ 45% District wide communication does not work properly for daily operation. The communication system used:

- 98% on telephone a fiber optics
- 1~2% by wireless

District 7 emphasized the problem caused by maintenance and construction. They complained for insufficient resources/engineers to maintain the system.

Possible ways for evaluation:

- Choosing certain locations which are working
- Providing support to District 7 to make the system 90% working before evaluation

However, District 7 provided a detailed list of loop detector stations and the communication system used to pass the data to TMC.

6.3 Preliminary Recommendations on Communication System

Some suggestions for reliable communication are:

- Using fiber optics or GPRS modem if possible
- Using TCP as communication protocol with resending capability if possible
- Automatic communication faults diagnosed at macroscopic and mesoscopic levels
- Professional staff regularly checking/reporting sensor and communication faults
- Regular and in-time system maintenance

Current traffic data are directly passed from control cabinet to TMC/PeMS. In a long run, traffic data system may need to be divided into three levels:

- TMC or PeMS
- Corridor
- Freeway/Arterial Sections

Communication system needs changing accordingly

- Short/medium range communication:
- Sensors and Control Cabinet ←→ Corridor Hub Computer and Database
- Long Range: Corridor Hub Computer and Database ←→ TMC or PeMS

Coordination between different Division within a Caltrans District

Coordination between Division of Caltrans District and maintenance contractors. After any road maintenance, Caltrans District electrical engineers responsible for loop detector station need to check if the engineers for the road maintenance have kept/restored the loop detector stations in working condition. A written report should be provided by the road maintenance contractors regarding the impact of the road maintenance on the loop detection health, before and after the work.

Chapter 7 Concluding Remarks and Future Study

Active Traffic Management in ITS Transportation System requires high quality of traffic data in different level. Here the high quality is the sense that the basic data from sensors should have sufficiently less error and time delay. Although, many traffic sensor detection technologies have been developed in recent years to satisfy this purpose, inductive loop detector stations are still the most invested and popularly used traffic detector system in California highway system. Loop systems, if installed properly and well-maintained, it would work reliably. Particularly, with the installation of dual loop stations and new technologies for loop detector cards, traffic data obtained from loop stations are improving. However, as any sensor detection systems, inductive loop detector system has defects and need maintenance. The main needs in this aspects are of two folds: (1) if the problem is intermittent and it only causes error in data temporarily, data correction method will be necessary to correct/cleanse those error automatically and generate healthy data; and (2) if the data error is persistent which is caused by some detector system faults, such fault need to be corrected by field traffic engineers. In both cases, it is necessary to have an effective portable loop fault detection tool that could be used for quickly detection loop system fault and isolate the problem. Most loop fault approaches developed in previous work were based on aggregated data analysis, which can be called indirect detection method. Although, it could be used to identify some detector faults, it is difficult to pinpoint out the exact problem and where the problem is. In addition, the high level aggregation approach obscure or covered the problem. Besides, the high level data are usually passed over by communication system, which could loss and/or pollute the data. Therefore such a loop fault detection approach could not isolate the problem from other problems.

This report focused on the Phase 1 and Phase 2 of the project: “Deliver a Set of Tools for Resolving Bad Inductive Loops and Correcting Bad Data”. The main tasks of this project were proposed in two areas:

- Developing Portable Loop Fault Detection Tool that compares synchronized loop data and vehicle by-vehicle tracking with video image data which provides at least a redundant sensor if not a ground truth automatically. If this is used for offline processing, image based vehicle detection does provides a ground truth;

- Developing strategies for systematic loop fault detection and data correction methods that could be used to cure some loop data problems at the control cabinet level.
- Preliminarily investigating the problem in communication system;

The first two phases of the project has achieved the expected goal as indicated in this report. We have conducted real-time demonstration for comparison of the loop signals from the control cabinet and the information from vehicle tracking using video camera on freeway.

The remaining tasks to be conducted under the new RTA will include:

- Refining the strategies for systematic loop fault detection as listed in Table 4.1;
- Systematic loop fault detection according to the strategies;
- Systematic data correction algorithm development in control cabinet level to provided to provide improved quality of data even if certain type loop faults appear or data error caused by some external uncertainties to the system;
- Systematic consideration of communication system based on the information obtained from three Caltrans districts;
- Providing recommendations to Caltrans Headquarters on
    - Strategy, method and a portable tool for systematic loop fault detection
    - Strategy and method for data correction at control cabinet level
    - Establishing a reliable communication system for traffic data passing

For convenience, we will use Berkeley Highway Lab section and facility for loop fault detection, data correction and preliminary communication system investigation. For extensive consideration of communication system, we will continue work with Caltrans districts for data and other information to conduct detailed data analysis. It is expected that in the end of the new RTA project, milestone will be setup in traffic data quality improvement.

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Appendix 1 : Loop Sensitivity Test Record

Run #	Max Spd	Vehicle type	Road surface		Run #	Max Spd	Vehicle Type	Rod surface
1	10	Audi Car	dry		21	20		dry
2	10	Audi Car	dry		22	20	Ford WinStar Van	dry
3	15	Audi Car	dry		23	25	Ford WinStar Van	dry
4	15	Audi Car	dry		24	25	Ford WinStar Van	dry
5	20	Audi Car	dry		25	30	Ford WinStar Van	dry
6	20	Audi Car	dry		26	30	Ford WinStar Van	dry
7	25	Audi Car	dry		27	35	Ford WinStar Van	dry
8	25	Audi Car	dry		28	35	Ford WinStar Van	dry
9	30	Audi Car	dry		29	40	Ford WinStar Van	dry
10	30	Audi Car	dry		30	40	Ford WinStar Van	dry
11	35	Audi Car	dry		31	10	Ford WinStar Van	dry
12	35	Audi Car	dry		32	10	Ford WinStar Van	dry
13	40	Audi Car	dry		33	15	Truck tractor	dry
14	40	Audi Car	dry		34	15	Truck tractor	dry
15	45	Audi Car	dry		35	20	Truck tractor	dry
16	45	Audi Car	dry		36	20	Truck tractor	dry
17	10	Ford WinStar Van	dry		37	25	Truck tractor	dry
18	10	Ford WinStar Van	dry		38	25	Truck tractor	dry
19	15	Ford WinStar Van	dry		39	30	Truck tractor	dry

20	15	Ford WinStar Van	dry		40	30	Truck tractor	dry
Run #	**Max Spd**	**Vehicle type**	**Road surface**		**Run #**	**Max Spd**	**Vehicle Type**	**Rod surface**
41	10	Truck tractor	wet		61	35		wet
42	10	Truck tractor	wet		62	35	Ford WinStar Van	wet
43	15	Truck tractor	wet		63	40	Ford WinStar Van	wet
44	15	Truck tractor	wet		64	40	Ford WinStar Van	wet
45	20	Truck tractor	wet		65	10	Audi Car	wet
46	20	Truck tractor	wet		66	10	Audi Car	wet
47	25	Truck tractor	wet		67	15	Audi Car	wet
48	25	Truck tractor	wet		68	15	Audi Car	wet
49	30	Truck tractor	wet		69	20	Audi Car	wet
50	30	Ford WinStar Van	wet		70	20	Audi Car	wet
51	10	Ford WinStar Van	wet		71	25	Audi Car	wet
52	10	Ford WinStar Van	wet		72	25	Audi Car	wet
53	15	Ford WinStar Van	wet		73	30	Audi Car	wet
54	15	Ford WinStar Van ar	wet		74	30	Audi Car	wet
55	20	Ford WinStar Van	wet		75	35	Audi Car	wet
56	20	Ford WinStar Van	wet		76	35	Audi Car	wet
57	25	Ford WinStar Van	wet		77	40	Audi Car	wet
58	25	Ford WinStar Van	wet		78	40	Audi Car	wet
59	30	Ford WinStar Van	wet		79	45	Audi Car	wet
60	30	Ford WinStar Van	wet		80	45	Audi Car	wet