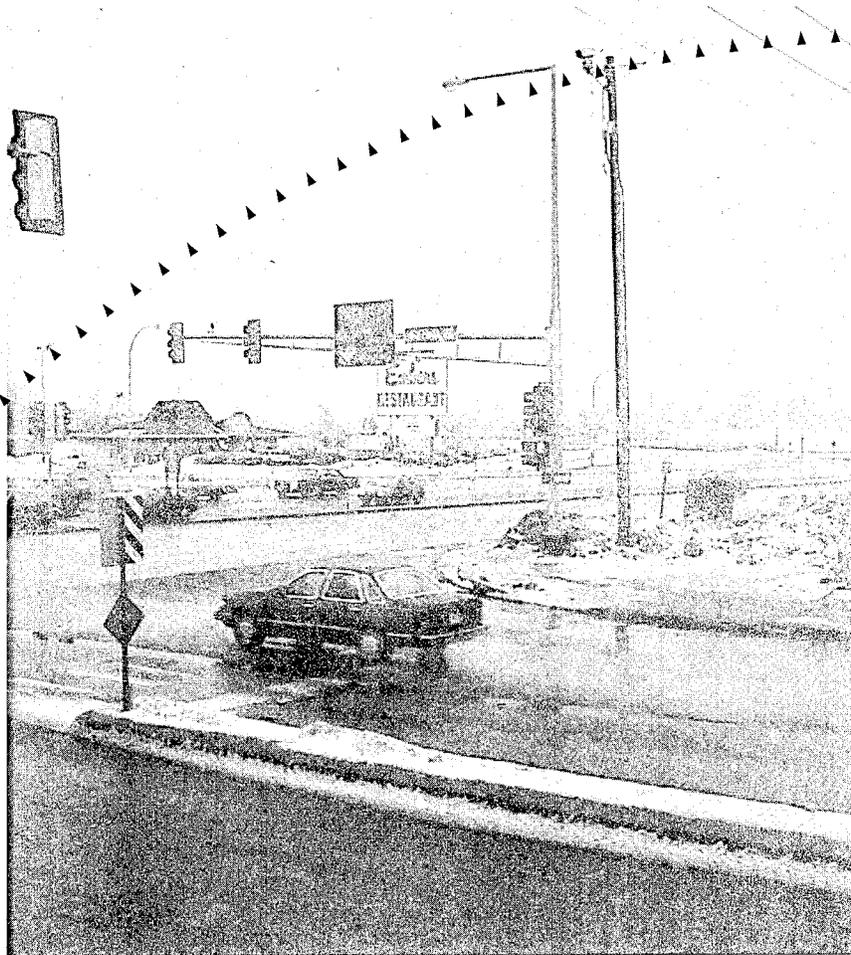




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# Maintaining the Traffic Control Systems

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# **MAINTAINING THE TRAFFIC CONTROL SYSTEM**

## **Final Report**

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## EXECUTIVE SUMMARY

This report discusses the development and implementation of new remote monitoring techniques to assist in the maintenance of modern traffic signals. Microprocessor-based traffic signals generate substantial information that can be used to assist in their maintenance. However, the information generated is quite substantial, and often perfectly good traffic signals generate status information. A significant effort is required to identify and isolate the information that actually corresponds to faulty behavior.

The efforts in this report are based on the premise that faults in a traffic signal affect the rate at which traffic flows through the intersection controlled by the signal. Conversely, anomalies in the traffic flow rate indicate the presence of a fault. The data from loop detectors, attached to the traffic signal, is used to estimate the rate of traffic flow. Anomalies in traffic flow are detected by comparing the flow at any instant with: (a) the flow through the same intersection during previous time periods; (b) the flow through intersections adjacent to the target intersection. We developed and implemented algorithms for hardware fault detection, based on traffic flow analysis, in a software system. The system also analyzes maintenance information generated by the traffic signals, and correlated it with anomalies in traffic flow. The system was tested on a set of signals generated by MnDoT. Its performance was tested by analyzing traffic flow during normal operation, and during periods when hardware faults were deliberately injected into the system. Our results demonstrated that:

1. The traffic flow through signals does achieve a steady-state under various operating conditions.
2. Faults in the traffic signal hardware can be detected by monitoring the traffic flow rate
3. Such a system can markedly reduce the time needed to process information generated by traffic signals for maintenance purposes.

The algorithms developed, their implementation, and the results obtained are discussed in detail in the report. The report also surveys previous efforts in remote maintenance of traffic signals.

# CHAPTER 1

## INTRODUCTION

An automatic traffic control system is a necessity in any large metropolitan area. Electric, and more recently electronic, traffic signals are the most common traffic control devices. A significant effort has been directed towards developing systematic techniques to place and efficiently operate traffic signals. However, installation and operation are only one component of a traffic control system. Effective maintenance techniques to quickly identify and repair faults are a second essential component. Malfunctioning components of a system degrade its performance. A faulty traffic signal not only blocks traffic at its intersection, but at other signals coordinated with it as well. While preventive maintenance is preferable, the large number of traffic signals make such an approach economically impractical. Hence, maintenance procedures are usually reactive. That is, the traffic authority responds to reports of malfunctioning signals. To minimize the damage they cause, malfunctioning or faulty signals should be both identified and repaired quickly. Once a malfunctioning signal has been identified, several agencies have developed systematic techniques for quick repair.

The longer a malfunctioning signal remains undetected, the more disruption it causes. It has been estimated that promptly identifying faulty units can provide a 100% return on capital[9]. When a malfunctioning traffic signal has been identified, even if repair is not immediate, temporary control measures such as all-way stop signs or the police, can be used to reduce the disruption to traffic flow. However, few techniques have been developed to quickly identify faulty traffic signals. In other words, very few techniques have been developed to minimize the delay between the times at which a traffic signal starts malfunctioning, and when the maintenance authority actually realizes its malfunctioning. Motorists' reports have been the traditional method to identify malfunctioning traffic signals. Such an approach has been recognized as being unreliable and more importantly prone to arbitrary and unpredictable delays. The wide availability of inexpensive computers and

telephone lines permits a more systematic method: remote monitoring, coupled with active identification, for the fast identification of faulty signals.

In this report, we will discuss the development and implementation of a system to automate the analysis of status and traffic flow data generated by modern traffic signals. Our techniques post-process event reports and detector data. The behavior of a traffic signal is compared with that of its neighbors, as well as with its own behavior in the past. The results of these analyses are used to assess the health of a traffic signal. The methods developed have been implemented in a prototype system. The system is designed to serve as a software assistant to the maintenance engineer by reducing the amount of time needed to locate and diagnose faults in a traffic control system. We also report results from the application of our techniques to a system of signals in the Metro region.

The rest of this report is organized as follows. Section 2 contains a detailed review of previous work in advanced traffic signal maintenance. This section reviews previous work in fault identification, remote monitoring and other techniques for automated signal maintenance. In Section 3, the current maintenance practices at the Minnesota Department of Transportation are discussed. The research executed in this project is discussed in Sections 4, 5 and 6. In Section 4, we discuss the development and implementation of a model to represent the traffic flow in the system. Section 5 describes the analysis techniques used to identify faults in the system. In Section 6, we discuss the results obtained when this system was applied to a sample set of traffic signals.

## CHAPTER 2

### PREVIOUS WORK

Traffic signal maintenance techniques have received significant attention in other countries. In discussing previous work, we concentrate on automated signal maintenance techniques implemented previously. Three systems are reviewed. The most comprehensive effort, a system in Britain is reviewed in detail. The literature surveyed in this report is limited literature the result of a search of several databases and the stacks at the University of Minnesota libraries. First, we discuss the common sources of faulty operation in traffic signals.

#### FAULT SOURCES

In this section, we attempt to understand why a traffic signal may malfunction. A fault, in a device, is a physical imperfection in the device. The physical fault can cause a device to malfunction, that is to function erroneously. When remote monitoring is used, it is only malfunctions, and not faults, which are visible externally. Given the large number of components in a traffic signal and its diverse functionality, attempting to identify all possible faults, and all the ways in which a device can malfunction is practically impossible. In general, it may be possible to identify the most common sources of failure. Consequently, we can also identify the malfunctions produced by common faults. That is, with traffic signals, we can identify the types of malfunctions commonly produced by faults. When monitoring a traffic signal remotely, if such a pattern of operation is noticed, it can taken as an indicator of the presence of a fault. In addition, the type of phasing may also provide diagnostic information.

Very little public documentation is available on the distribution of faults in traffic signals. The data from one old study on non-intelligent controllers[1] is shown in Table 1. This study indicated that nearly 70% of the faults in a signal were electrically detectable. This percentage is greater in modern signals[9]. In older controllers, faults are most likely to be permanent. That is, once they

occur, they will constantly produce the same errors for the same inputs. Modern systems are more complex and sensitive relative to older systems. Hence, intermittent faults are a more common occurrence[9]. This is especially true of newer detectors. An intermittent fault is one which produces errors only occasionally. Such faults are harder to detect, since they may not produce errors when the system is actually being observed. To correctly detect such faults, the system has to be observed not for an instant, but over a period of time. Many of the faults listed below could potentially have a direct impact on the flow of traffic. Conversely, by measuring traffic flow, one may be able to detect several fault types.

<i>Fault Type</i>	<i>Percentage</i>
Lamp burnout, signal unit, cable connection	55.1%
Faulty indication	19.9%
All or partial lamp out	7.8%
Pedestrian push button failure	5.7%
Power supply interruption	2.3%
Miscellaneous	9.2

Table 1. Fault Distribution in Old Signals

## REMOTE MONITORING TECHNIQUES

Remote monitoring techniques have been used since the mid-1970's[1]-[3]. The British have been the most active in this area, as well as the source of most public documentation[2]-[9]. We will also review a paper published by a Japanese traffic control agency[1].

### BRITISH TECHNIQUES

A concise description of the remote monitoring effort by the Greater London Council(GLC) is found in [5]. The monitoring system consists of two components. The first is the hardware and software installed at the central control facility. The second is the hardware, and software, installed at each monitored signal. This hardware is referred to as the Outstation Monitoring Unit (OMU). While the central system is also described in [5], the functionality of the OMU is described in [6].

### The Outstation Monitoring Unit

The OMU is a unit which is attached to each traffic signal. OMUs have been designed for several controllers, such as simple timed controllers, more complex solid-state controllers, as well as microprocessor-based controller. The OMU monitors the controller itself, as well as the devices which send inputs to the controller. Faults in the various units are detected as follows:

- Faults in the detectors and push buttons are detected by monitoring maximum and minimum presence. Sometimes, this approach leads to false fault indicators.
- The current drawn by the signal lights, as well as the input voltage, are monitored to identify faults in traffic lights. Since the current drawn by good lights can vary over their lifetime, some tolerance is required.
- The inputs to the controller, from external devices, are checked by the comparing them with the inputs to the OMU. A mismatch indicates that the wires leading to the controller may be faulty.
- For simple controllers the OMU checks detector/phase correlation. That is, the OMU checks that the controller responds accurately to information from the detectors.
- For microprocessor-based controllers with a large number of plans, this approach is not possible. The OMU relies on the self-checking features of the controller.

The OMU also possesses software to interface with the controller, and implement the monitoring functions. The devices has been designed to accept software upgrades. The data recorded by the OMU is also logged. The OMU communicates with the central facility through leased telephone lines. The OMU initiates communication when a fault is detected. However, to clear software the central facility communicates with the OMU periodically.

### Central Facility Hardware:

Several general purpose computers are used at the central facility. One computer is used to store the data generated from OMUs, as well as to execute interrogation sessions. The remaining computers are used to interface with the database.

### Central Facility Software

The software at the central facility is designed to perform maintenance and administrative functions. First, we review maintenance functions:

- The database receives reports from OMUs, interrogates OMUs, and also resets OMUs for correct operation or after a fault has been detected.
- The database contains information about each traffic signal, such as its type, location and phase settings.
- The database also records the maintenance history, as well as the action taken after each fault report, and prioritizes fault reports.
- The software also provides a friendly user interface which also permits interrogative searches.

The administrative functions are not reviewed here for brevity. Readers are referred to [5] for more details.

### Maintenance Contract

The maintenance functions were not performed by the GLC, but by private contractors. The contractors had access to the data generated by the central facility software from remote locations. The actual maintenance contracts are beyond the scope of this project. Again, readers are referred to [6,8] for more details on this topic.

## **JAPANESE TECHNIQUES**

The Japanese traffic control agency employs remote monitoring techniques on a national basis[1]. In many respects, the Japanese technique is similar to the British approach. Hence, details are reviewed only briefly. The remote monitoring technique in [1] is based on monitoring the current drawn by the signal, the status of the controller, and the inputs from the sensors. The faults that are detected include lamp burnout, incorrect phase timing, incorrect indication, conflicting greens, or detector/push-button malfunction. Lamp-related problems, such as conflicts, are detected by the monitoring power supply current. Detector problems are identified by timing maximum/minimum presence. The phasing of the controller is monitored by timing each of the controller phases. Any deviation from normal values indicates the presence of a fault. The first cycle after power-up is used to determine what "normal" values are. The monitoring unit is an external hardware unit mounted on each signal, and interrupts the path from the controller to the lamps, and from the detectors to the controller. Any information on faults is transmitted to a local fault monitoring station, and on to a regional fault monitoring station. The communication between the signals and the central controllers may either be wireless, or on leased telephone lines. Information on present remote monitoring techniques in English language journals has not been found, in spite of an extensive database search.

## **EXPERT SYSTEMS**

Expert systems are large complex software systems designed to incorporate the knowledge of skilled individuals. An expert system is designed to combine the skills of an expert with the speed of automation. As with other complex problems, expert systems have been suggested and developed for many problems in traffic control[10]-[17]. All expert systems process any data generated by the control system such as detector data, plan switches, and camera images. The goal of most expert systems is to assist engineers in the management of incidents which may disrupt traffic.

To our knowledge, only a single expert system has been designed for control system maintenance[18]. The signal complaint aid for dispatchers (SCAD): an expert system. SCAD is

designed to assist dispatchers in diagnosing a traffic signal complaint. SCAD is not a proactive remote monitoring system. Rather it is used by a dispatcher when responding to a call from a road user. The goal of the system is to enable unskilled operators to elicit the knowledge that would be requested by skilled engineers. When a call is received, its processing is divided into three phases. The first phase, a contact-interrogation phase helps the dispatcher ask the right series of questions. The second cause analysis phase uses the information gathered from the caller, as well as the history of the target signal, to identify the most probable causes of malfunction. The third, notification phase, notifies the appropriate repair organizations. The SCAD system has been written in the BASIC programming language and executes on an IBM PC. An initial knowledge accumulation phase, where SCAD gains an understanding of the traffic signals being monitored, is required. In addition, SCAD also consumes large amounts of memory.

## **DISCUSSION**

In this section our goal is to analyze previous remote monitoring efforts in the context of our research effort. First, we analyze previous efforts in terms of benefits and costs. Next, we discuss the relevance of past work to our research. The section concludes with a review of the potential benefits of successful completion.

In the successful remote monitoring efforts in Britain, both the processes of detecting faults, and managing the information generated have been given equal importance. The database at the central facility which maintains a global perspective of the system is as important as the collection of OMUs at individual traffic signals. Secondly, fault detection is active rather than passive. That is, when a fault occurs in a signal, its OMU does not simply passively log the result. Rather, it contacts the central facility. As can be expected, in the large GLC system, the OMUs generate a tremendous amount of data. The software at the central facility organizes this data. However, according to published results, the data generated from the OMUs is not processed or analyzed in any manner. This drawback limits the system in many ways.

- For simple controllers the OMU checks detector/phase correlation. That is, the OMU checks that the controller responds accurately to information from the detectors.
- The diagnostic capabilities of the system are limited to the information generated by the hardware. However, by correlating information from multiple sources, it may be possible to improve the diagnostic capability.
- Improper settings, and transients during normal operation, cause the OMU hardware to generate "false" fault reports. Unfortunately, these reports are given the same credence genuine reports are given. Too many false reports will involve an unnecessary expenditure of labor and time and reduce the effectiveness of the system. Such false reports are also common with many modern traffic signals and are a source of annoyance.
- The ability to detect intermittent faults is extremely limited[9]. Intermittent faults are usually active only in certain periods. If the on-site maintenance visit does not coincide with the active period, repair may be very difficult. Again, post processing may identify the best period to visit the signal.

The expert system approach, discussed above attempts to reduce on-site maintenance time by eliciting information from the complainant. However, expert systems are usually only as good as the rules used to generate the expert system. Additionally, unlike the hardware-based remote monitoring systems, the expert system has been designed to respond to complaints, rather than to seek faults. Secondly, the expert system is heavily dependent on data provided by non-expert commuters.

Remote monitoring techniques have received more attention in other countries than in the United States. Remote monitoring facilities make information that would normally not be available, accessible to a maintenance engineer. Successful remote monitoring efforts have been implemented in Britain and in Japan. The former effort was reviewed in detail in this report. In the British effort, it was shown that the proper organization of detection data is at least as important as

the remote monitoring functions. Also, their system is limited in its ability to detect intermittent faults. Current traffic signal systems in the Metro area support integral remote monitoring features. However, the data generated by these signals is used in its raw format, and not processed in any way.

## **CHAPTER 3**

### **CURRENT MAINTENANCE PROCEDURES**

A review of current maintenance techniques for traffic signals will help place the research reported in this report in context. First, we describe the features of a typical signal system relevant to our research. Next, we discuss the remote monitoring features currently available and used. The section concludes with a brief review of a typical maintenance cycle.

#### **SYSTEM STRUCTURE**

Modern signal systems can be electronically observed and controlled from a central facility. Communication between the main station and a set of signals is through the telephone lines. Signals in the system are arranged in a hierarchical fashion. On large highways signals are typically organized in "zones". Each signal in a zone has an individual controller. One of the signals is designated as the "zone master". The zone master also contains the programming necessary to coordinate the operation of the signals in each zone. All communication between the zone and the main station is done through the zone master.

#### **REMOTE MONITORING FEATURES**

Many microprocessor-based traffic signals support limited integral remote monitoring functions. It is reasonable to believe that one can derive information on the health of various components from this information without increasing the cost of each signal. A signal system generates a substantial amount of data that provides a traffic engineer with information about system operation, such as incidents that disrupt normal operation and traffic flow patterns. The signal also provides information that may assist in maintenance. The controllers generate two types of data. One is called an "Event Report". This represents the behavior of the signal. The second set of data is the "Detector Log". This represents traffic flow information.

An incident which should not occur during normal operation of the traffic signal is called an "event". Events are stored in zone master controller memory as they occur. They are stored in prioritized list. The priorities assigned to events are determined by traffic control engineers. For example, in signals supplied by the Econolite corporation, the local microprocessor tracks a variety of events which include among others:

- The number of vehicles counted by various detectors
- Coordination errors or alarms
- Plan switches
- Flashing lights
- Devices going on and off line

Typically, events are reported immediately to the main control computer when they have priority of 1, or following a priority 2 event delay time out. Priority 3 events do not get reported until a priority 1 or 2 event is reported. Events are also automatically transferred if the number of events in the zone master controller, that is the number stored, exceeds 200. Events reported by a zone master are stored on a separate hard drive at the main computer. A separate file is created for each zone for each day.

## **TRAFFIC FLOW INFORMATION**

The flow of traffic in the system is monitored by a set of loop detectors. Loop detectors are installed under the pavement on the approach roads to the junction controlled by a signal. Information provided by these detectors is used to control the operation of individual traffic signals, and to coordinate the interaction between the signals in a zone. A detector can be attached to a counter such that the combined unit is capable of counting the number of cars that pass over it, as well as the duration of time for which the portion of the road above the detector was occupied. They are subject to a significant amount of stress that causes them to often malfunction. A significant problem with detectors is that access to them is limited. Thus, one cannot easily directly

verify if it is working properly. Fault detection can only be indirect: by analyzing the data produced by the detector.

Detectors may either be local detectors or system detectors. Local detectors, are attached to a specific signal in the system, and are used to control signal operation. Traffic flow information provided by local detectors cannot be directly logged. That is, the information cannot be recorded for later use. System detectors log continuously at the zone master after being assigned to logging. Typically data is gathered in 15 minute intervals. The "Detector Log" is the accumulated vehicle volume and occupancy information at each intersection in the zone on an hourly basis. Typically, the master log is transferred to the main computer following a schedule set up at the zone master. Currently, a single master provides the ability to count the traffic only at a fixed number of detectors. In other words, not all detectors can be designated to be system detectors. In modern systems, Detectors can be dynamically re-designated to be system detectors. This is not true in older systems. In advanced controllers, detectors can be remotely re-designated as the system detectors by the operator. In older controllers, the designation of detectors is hard wired into the system.

## **MAINTENANCE PROCESS**

The rest of the discussion in this report focuses on Econolite signals since they will be the target test signal system. The controller and the monitoring software used for the study were the ASC/2 and the "zone monitor" software, both from Econolite corporation. Econolite provided us with a complimentary copy of the control software. These signals may be used in either an active or passive mode. Current maintenance procedures mainly utilize the passive mode. The maintenance is conducted as follows:

1. At each signal system, all the events recorded are stored in local memory at each controller.
2. Once a day, each signal is polled by the central facility. The signal "dumps" all its events into the central controller.

3. The event lists from ALL the signals is printed out sequentially in a completely unformatted raw form.
4. The event list is usually several tens of pages long and contains hundreds of single spaced block-typed entries.
5. The maintenance engineer scans the list visually to identify events which may be caused by faults. This is a very time-consuming process.
6. If a suspicious sequence of events is found, the engineer follows-up with a visual inspection of the suspicious signal.
7. Data in detector logs is not currently used for maintenance procedures since it is difficult to understand.

Clearly, modern Econolite signals provide tremendous amounts of information. Current maintenance procedures do utilize the information generated. However, when a large number of signals have been installed, the maintenance engineer is burdened with too much information rather than too little information. Further, with the present approach, the detection of intermittent faults is very difficult. In summary, post-processing data is important in a system with a large number of "intelligent" signals. If the data generated is not processed in any way, an engineer will be deluged with too much information.

# CHAPTER 4

## MODEL CONSTRUCTION

Our basic technique is to process the information generated by a traffic signal, that is the event reports and traffic flow information, and generate useful maintenance information. The traffic flow information will be used to verify if the signal is processing traffic at a normal throughput. In a zone, one malfunctioning traffic signal may affect the throughput of other signals in the zone as well. Thus, observing the system as a whole will be helpful for fault detection. The first step in such an analysis is to construct a system model that represents key features of interest.

### MODEL DEVELOPMENT

A model has to coordinate traffic flow information with the status reports generated by signals. In addition, the flow in a system as a whole has to be represented, not just the flow through individual traffic signals. To address these needs, our model represents four characteristics

- Traffic signal behavior: The behavior of the traffic signal is represented by the status and event reports generated by the zone controllers. The event reports are an indicator of the health of the individual controllers.
- Detector data: Detector data are stored in zone master log files. The counters provide vehicle counts for the detectors being monitored. A zone master cannot simultaneously monitor counts in all the detectors in the system.
- Geographical characteristics: Geographical characteristics to be represented are the positions of various signals in a zone, and the positions of traffic detectors in each of the zones.
- Time: One of our goals is to monitor the activity of a traffic signal across time. The model should be able to “segment” the data into various time slices.

## **MODEL IMPLEMENTATION PROBLEMS**

Our model had to combine information from at least three different sources. Thus, implementing the model was not a straightforward task. Next, we briefly review the difficulties encountered in implementing the model. We encountered difficulties in representing all three characteristics, signal behavior, traffic flow data and geographic information in one database.

### **EVENT REPORT INFORMATION**

Event report information is readily accessible through the on-line Econolite database. However, it is stored in proprietary binary, rather than text, format. We required the ability to access the event reports outside the Econolite database. We performed two tasks to access even report information:

1. Obtained a traffic of the zone controller software from Econolite corporation for no charge.
2. Reconfigured a PC, and developed a method to convert the binary format to ASCII text stored inside a computer. This essentially involves executing a fake print operation on the event report, capturing that information on an output port of the PC and converting the information back to readable text.

### **DETECTOR COUNT INFORMATION**

Obtaining and utilizing information from the system and local detectors proved to be the most difficult component of model construction. We faced two problems in incorporating detector information.

The first problem was in accurately identifying information. The detector logs contain only numerical and no text information. The choice of detectors to be monitored, and the mapping of detectors to individual counters in the controllers is made by the controlling traffic engineer. Hence, to decipher detector data, information is required from the traffic engineer. Else, the information generated will be meaningless.

The second problem was in our ability to collect detector count information. In fact, this problem forced us to switch from a test corridor on T.H. 55 in the West Metro, to a signal system on T.H. 13 in the East Metro. The latter was monitored by an old set of controllers. In the older KMC-1000 controllers, once fixed, the designation of system detectors cannot be changed without altering the hardware. This is an undesirable situation. Engineers at Econolite corporation advised us to switch to newer A series controllers. In these newer controllers, detector-counter map can be changed in software.

## **GEOGRAPHIC INFORMATION**

Geographic information on the position of traffic signals was obtained from a map, and incorporated into the database. Information regarding the location of individual detectors was obtained from Mn/DOT spread-sheets, and also incorporated into the database.



## CHAPTER 5

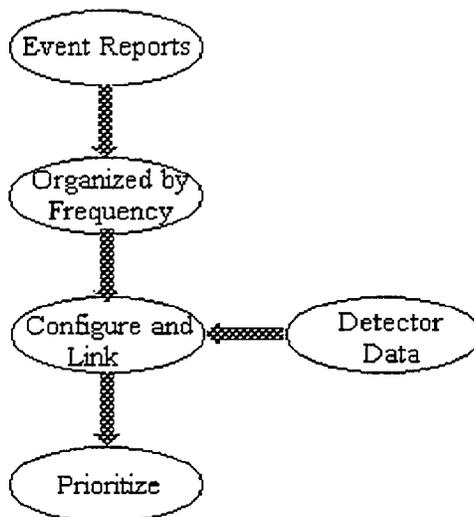
### ANALYSIS PROCEDURE

The aim of our analysis procedure is to combine system status information, generated by the traffic signal, with traffic flow information, generated by the detectors, and identify potentially faulty components. Figure 1 shows a block diagram of our general analysis procedure. It works as follows:

1. The first step in our analysis procedure is to construct a model of the system, convert the event reports to a readable format, and attach them to the model.
2. The events recorded are classified in terms of location and frequency of occurrence. Events which have been reported very infrequently are given a low priority since they probably correspond to transient situations. After this step, there still remain a large number of event reports to be prioritized.
3. The traffic flow data is to be analyzed in various formats. The system detectors are chosen so as to enable traffic flow measurement in various configurations. Note that our analysis is only based on the number of vehicles reported by detectors, that is the traffic counts, and does not use the occupancy information generated by detectors. Several configurations under which traffic flow can be analyzed are discussed in more detail below.
4. The analysis uses geographical information on the location of traffic signals and cycles in traffic flows. With both approaches, our goal is to generate data which represents normal traffic flow in the system. This data is used as the "gold standard".
5. Data gathered during monitored operation is compared with the "gold standard". If the traffic deviates by greater than a predetermined threshold, the flow is tagged as anomalous.

6. Given an anomalous traffic flow pattern, a corresponding event report can potentially confirm the presence of a fault and may even indicate what is wrong with the signal.
7. Even if no event was reported, it is worth examining the signal to verify the cause of the anomalous flow.
8. All anomalous traffic flows and high event frequencies are tagged as a list of potential faults.
9. Generate a list of potential faults with links to the corresponding data in the traffic flow information and event reports.

Such a system would be used to process the daily data generated by traffic signals. Note that the time needed to actually process data is negligible.



*Figure 1. Analysis Procedure*

## **TESTBED SYSTEM**

As discussed above, in order to collect data under multiple traffic flows, we needed access to advanced ASC/2 controllers. The study was done on a zone of four intersections on Trunk Highway 13, where the signals were controlled by an advanced system. The intersections were:

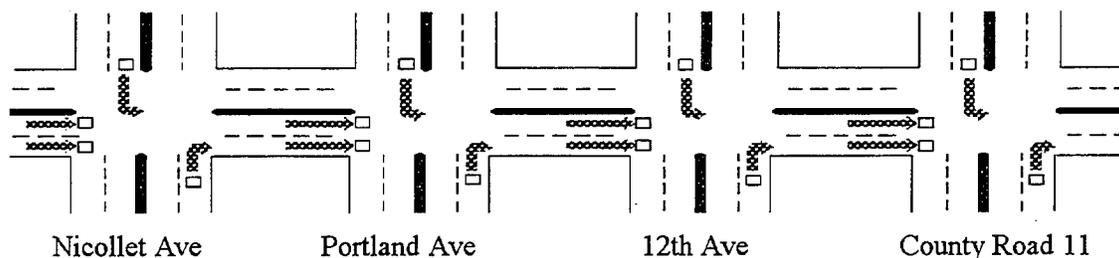
1. T.H. 13 with Nicollet Avenue

2. T.H. 13 with Portland Avenue
3. T.H. 13 with 12<sup>th</sup> Avenue
4. T.H. 13 with County Road 11

## GATHERING TRAFFIC FLOW DATA

All four intersections were coordinated with one another and master controller, the “zone master” is located at Portland avenue. In order to assess the health of the system, the traffic flow under various conditions has to be gathered. Recall that traffic flow data can only be gathered for detectors, designated as system detectors. Therefore, to gather a particular data set, the set of system detectors will have to be chosen appropriately. The set of system detectors will have to change according to the flow pattern desired. In other words, our system requires a signal system in which system detectors can be remotely reprogrammed. With modern controllers, one can make changes in the system logging detector from the central zone using the Zone Monitor software. This is not possible with relatively older controllers where all the logging detectors are hardwired.

For example, in Figure 2, the detectors provide counts for all the vehicles traveling east through the system. The arrows in the figure correspond to detectors which are designated as system detectors. After gathering data for some time, one can determine what constitutes normal traffic flow patterns in the system. The system developed was tested under several conditions. First, we demonstrate that under normal traffic flow conditions, the traffic flow data behaves as expected.



*Figure 2. Example Configuration*

## GEOGRAPHIC ANALYSIS

Geographic analysis is based on the idea that a single fault will cause a signal to process traffic at a much slower rate than its immediate neighbors. That is, the faulty signal will be the “bottleneck” for traffic flow in the system. For example, for the configuration shown in Figure 2, assuming all the intersections are similar, the incoming traffic at each intersection should follow a steady pattern. One method of representing normal traffic flow is by dividing the traffic at one intersection with the traffic at its immediate neighbor. Figures 3a, 3b and 3c represent the ratio of counts at three adjacent intersections on 4/22/96. From the figures, one may notice that flow through the system is smooth as all the ratios are within 0.15 of unity.

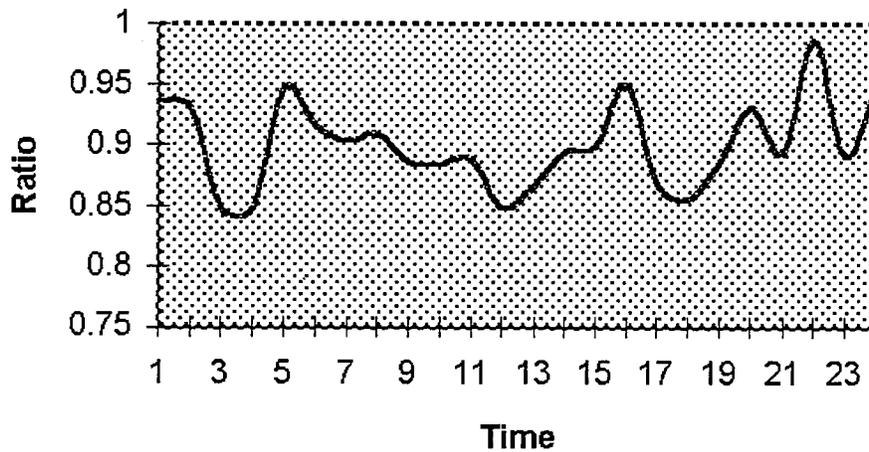


Figure 3(a): Normal relative traffic flow at adjacent junctions  
T.H. 13 with Nicollet vs. T.H. 13 with Portland Avenue

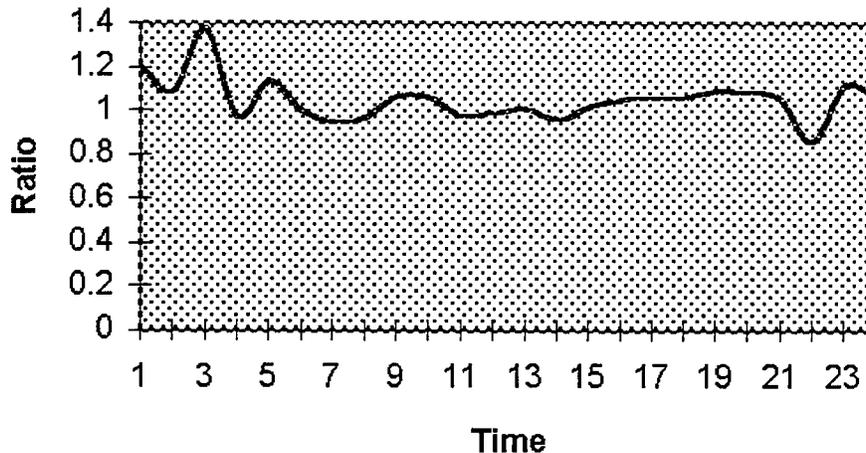


Figure 3(b): Normal relative traffic flow at adjacent junctions  
T.H. 13 with Portland Avenue vs. T.H. 13 with 12<sup>th</sup> Avenue

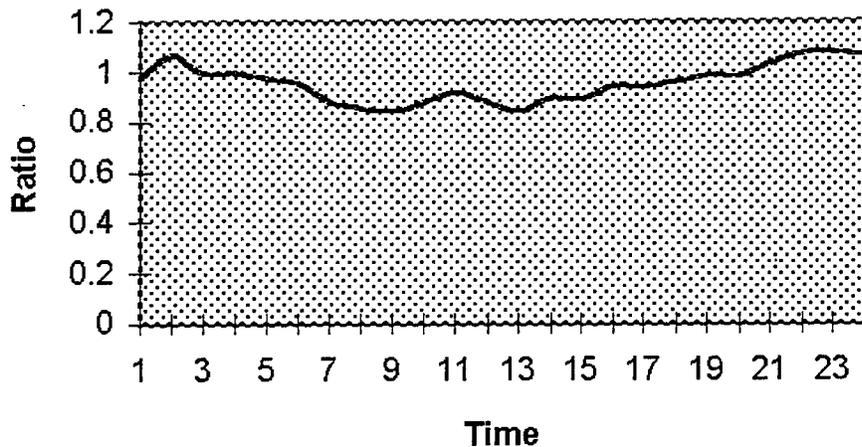


Figure 3(c): Normal relative traffic flow at adjacent junctions  
T.H. 13 with 12<sup>th</sup> Avenue vs. T.H. 13 with County Road 11

This pattern is then stored to serve as a reference for future data. The new incoming data is compared to it. Any deviation from normal behavior represents a potential fault within the system. The data within Figures 3(a), 3(b) and 3(c) represent normal behavior, that is the “gold standard” with which traffic flow on other days is compared. Based on this data, we may set a deviation of 0.2 from the average as the threshold for fault detection. If the observed ratios vary by more than 0.2, then one may flag the data as indicating the presence of a fault.

## HISTORICAL ANALYSIS

The same technique can be used to do historical checking of traffic flow patterns. That is, the current flow pattern can be compared with the flow pattern from a previous week. Figures 4(a), 4(b) and 4(c) show the patterns from a week earlier on 4/15/96. When compared, the two sets of patterns were found to be nearly identical, and the margin of variation was also identical. The same correlation in historical data may be observed in traffic flow at a single intersection. Figure 5 compares the traffic flow at the Nicollet avenue intersection over two days separated by a week. As can be seen, the flow is nearly identical.

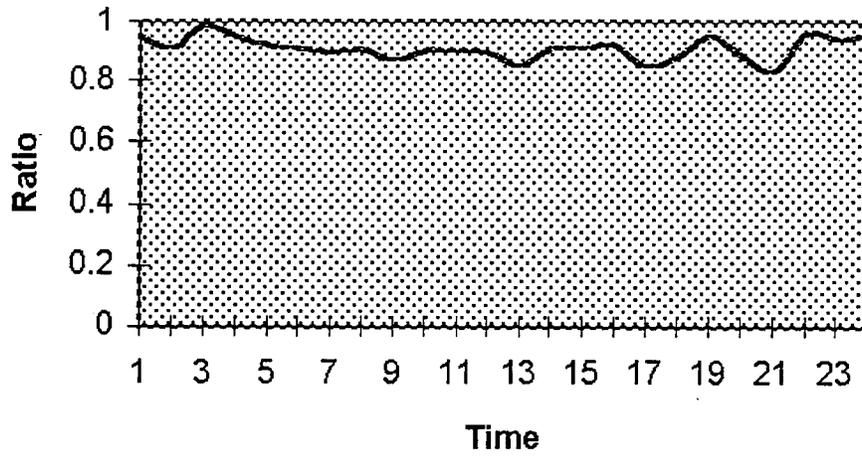


Figure 4(a): Traffic ratios for 4/15/96  
T.H. 13 with Nicollet vs. T.H. 13 with Portland Ave.

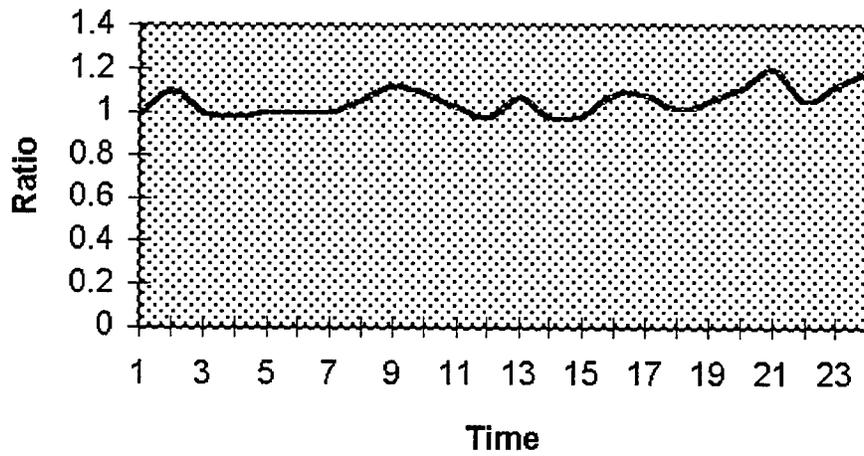


Figure 4(b): Traffic ratios for 4/15/96  
T.H. 13 with 12<sup>th</sup> Ave. vs. T.H. 13 with Portland Ave.

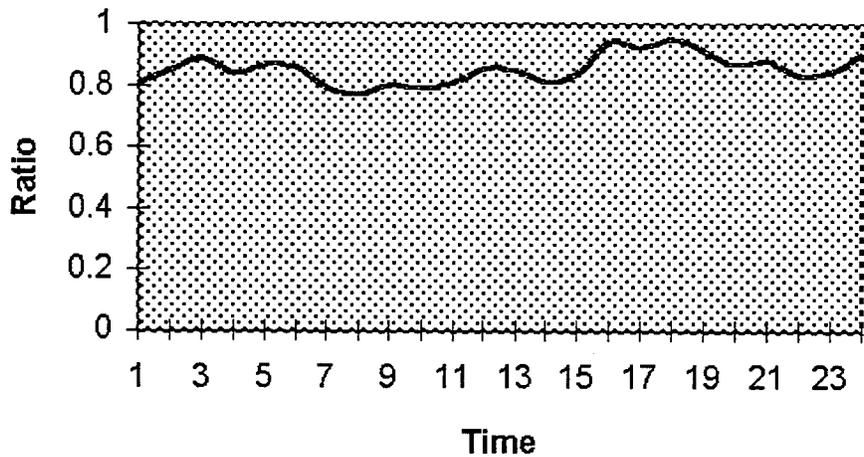


Figure 4(a): Traffic ratios for 4/15/96  
T.H. 13 with 12<sup>th</sup> Ave. vs. T.H. 13 with County Rd. 11

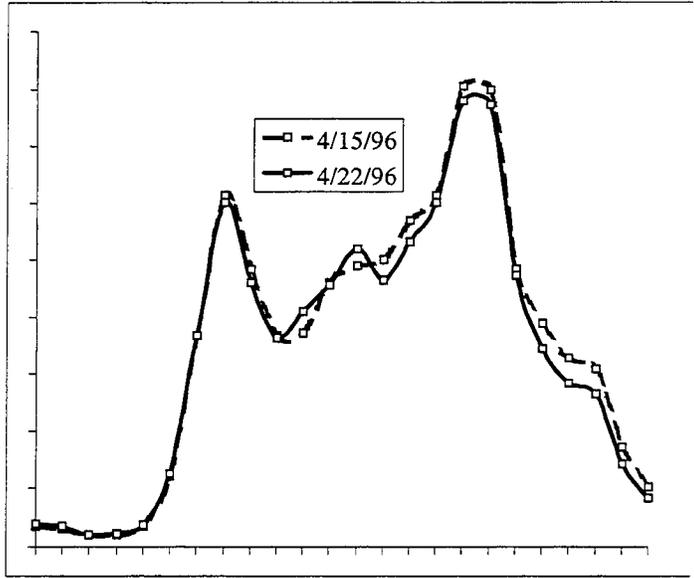


Figure 5: Comparing traffic flows across one week  
T.H. 13 with Nicollet Avenue



## CHAPTER 6

### RESULTS

Our prototype system was tested under a variety of fault conditions. First, we report results for a fault condition that occurred during normal operation. However, faults do not naturally occur at a rapid rate during normal operation. Thus, we had to resort to active measures. The last two are results observed with artificial fault injection. That is, faults were deliberately injected into the system, to verify if the fault impacted traffic flow, and the impact could be detected by our system.

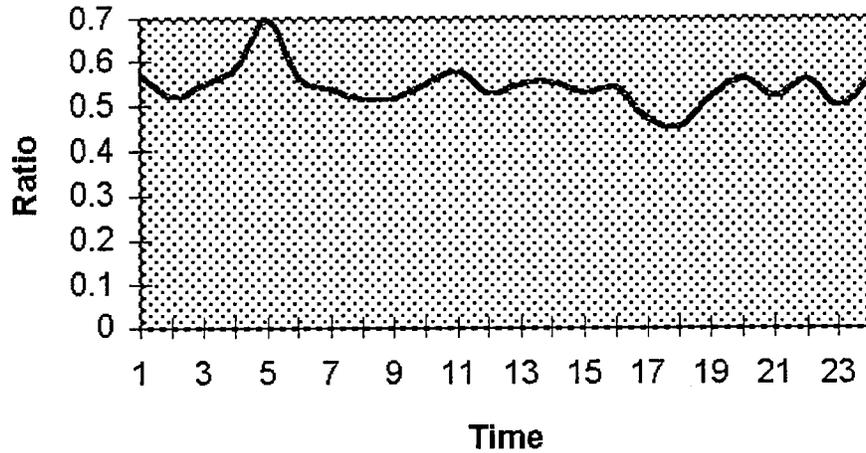
The three conditions are:

1. A detector fault at one intersection
2. A flashing red at one intersection
3. A stuck push-button at one intersection

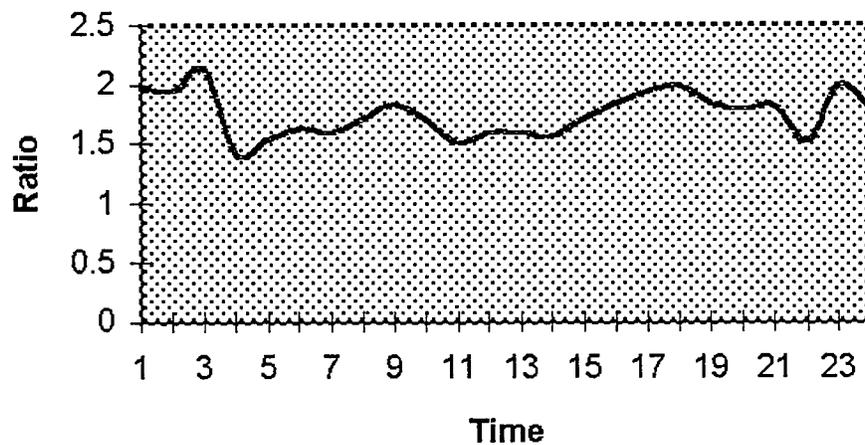
These faults were injected by Mn/DOT personnel (Mr. Bob Betts, Mr. J. Katzenmacher, Mr. M. Nookala). The time needed to process the data for all these faults is negligible.

#### **FAULT EXAMPLE 1 - DETECTOR FAULT**

The first fault considered here was detected simply by monitoring the traffic signal and processing the data obtained. The data in Figures 6(a) and 6(b) represent the patterns obtained on 4/26/96. The ratios changed substantially from their expected values. (The expected values are those logged on 4/22/96). Even with a quick visual inspection, one may notice a large change in the traffic ratios at these two intersections. The ratio of traffic counts between 12<sup>th</sup> Ave. and County Road 11 did not change from the previous case.



*Figure 6(a): Traffic ratios for 4/26/96  
T.H. 13 with Nicollet vs. T.H. 13 with Portland Ave.*



*Figure 6(b): Traffic ratios for 4/26/96  
T.H. 13 with 12<sup>th</sup> Ave. vs. T.H. 13 with Portland Ave.*

The same impact on traffic flow can be observed by comparing the traffic patterns across the two days of interest, at the Portland avenue intersection. That is, the traffic on 4/26/96 is compared with traffic on the “standard” day 4/22/96. Figure 7 compares the traffic flow at this junction across the two days. One may observe that the traffic flow on 4/22/96 at the intersection is much higher than the traffic flow on 4/26/96. This impact is visible through out the entire day. The findings from the above analysis were confirmed by searching the event report for that intersection at that moment of time. The event report contained a long sequence of events.

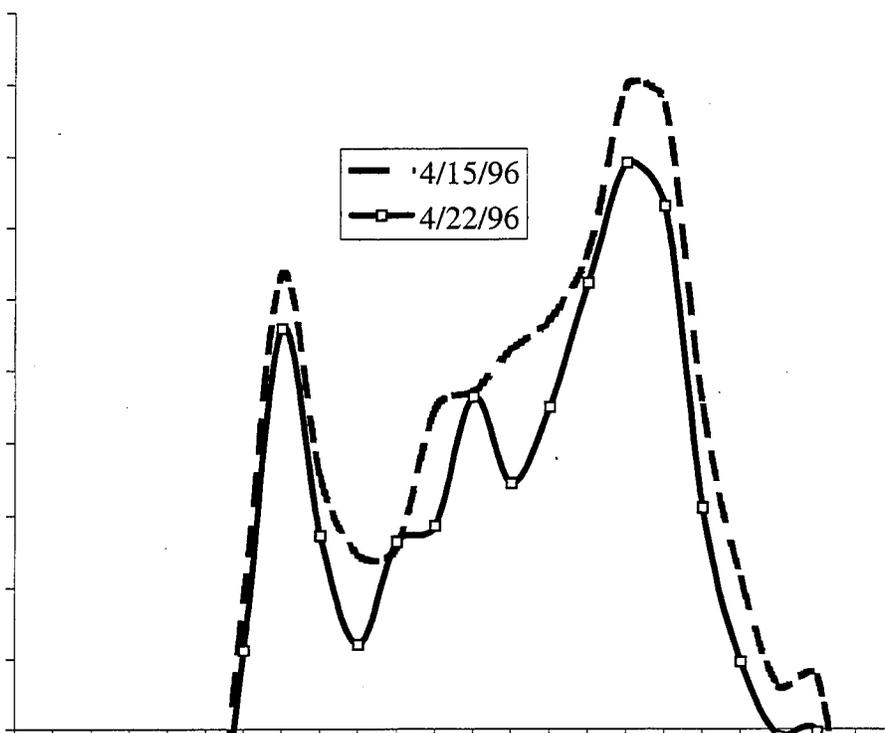


Figure 7: Traffic ratios for 4/22/96 and 4/26/96  
T.H. 13 with Portland Ave.

On 4/26/96 after detecting abnormal traffic flow, when the event report of the day was searched, it was found that a system detector on Portland avenue was off line. Therefore, this detector did not report any traffic flow and this resulted in the anomalies that were observed in the traffic flow. However, since actual traffic flow was not affected. In other words, the two remaining intersections were also not affected by the fault at the Portland avenue intersection. Therefore, we did not observe any anomaly in the traffic flow at those two intersections. Readers may note that this fault is not a high priority fault. *This can only be detected by going through the set of weekly event reports.*

## FAULT EXAMPLE 2 - FLASHING RED SIGNAL

As an extreme example of anomalous operation, the signal controlling the intersection of T.H. 13 with 12<sup>th</sup> Avenue was deliberately set to flashing red. In other words, the intersection was effectively converted to a four-way stop sign. Traffic on T.H. 13 is normally much higher than that

on 12<sup>th</sup> Avenue. Correspondingly, during normal operation, the traffic on T.H. 13 is given a very high priority. However, a flashing red gives both signals equal priority. Therefore, traffic on T.H. 13 will be slowed by a flashing red. This is indicated by the data in Figure 8. This figure compares traffic on T.H. 13 through the intersections on two days, one affected by the fault on 8/29/96, and the other during normal operation. As can be seen throughput drops sharply. The impact however was not as large as one would expect from such a catastrophic condition. This may be explained as follows. Our testbed was a part of a construction zone for both the test days. This slowed traffic through the entire system. However, the impact of the flashing red was substantial enough to affect even the lighter traffic flow. However, this event is already reported as a high priority event by a traffic signal.

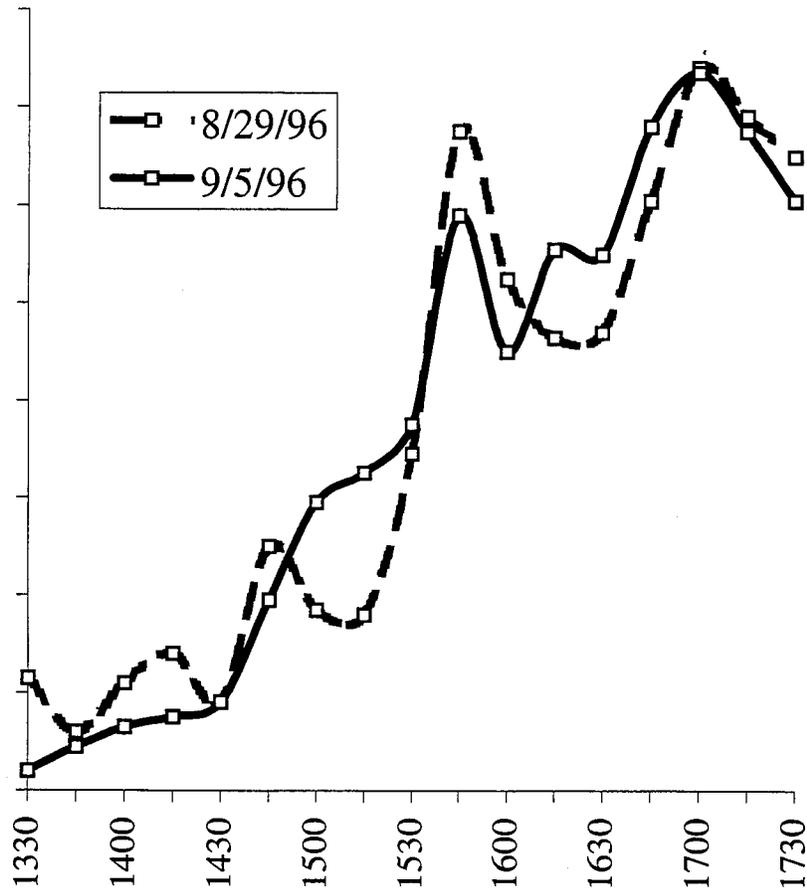


Figure 8: Traffic ratios for 4/15/96  
T.H. 13 with Portland Ave.

### FAULT EXAMPLE 3 - PEDESTRIAN PUSH BUTTON FAULT

The last fault injected was a pedestrian push button fault at the intersection of T.H. 13 with 12<sup>th</sup> Avenue. The push button was permanently stuck on call. The permanent call has the effect of altering normal signal cycles. The exact impact depends on the which push button at an intersection is stuck. With any fault, since the cycle is altered, in the presence of heavy traffic, the flow of traffic should be impeded by the fault. However, unlike a flashing red signal, this fault will not affect light traffic flow, because its impact is more subtle.

Unfortunately, when the fault was injected, as mentioned above, our signal test bed was a part of a construction zone. The construction impeded traffic flow and hence it was impossible to judge the impact of the push button on traffic flow. However, recall that our tool also tracks event reports from each traffic signal. A push button fault will result in a large number of coordination errors. These coordination errors occur because of the impact of the push button on the operating cycle.

The event reports, about the target intersection and its immediate neighbor, are shown in Figure 9. As can be seen, compared to its neighbor, the target intersection generates a very large number of events. This abnormally high sequence can be used to alert the traffic engineer. This sequence of events can only be detected by reading the set of weekly reports, a time consuming process.

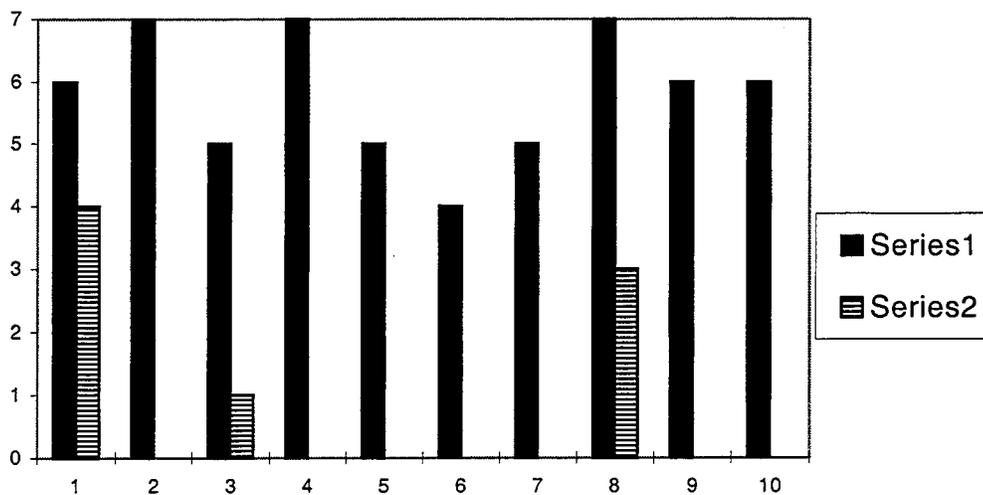


Figure 9: Event report frequency for push-button fault  
T.H. 13 with 12<sup>th</sup> and T.H. 13 with Portland



## CHAPTER 7

### CONCLUSION

This report discussed the development and implementation of a software assistant to aid in the remote monitoring of traffic signals. This report surveyed the state of the art in automated maintenance techniques for traffic signals. Remote monitoring techniques in Britain were reviewed in detail. We also briefly discussed current maintenance practices in Mn/DOT, and the capabilities offered by modern traffic controllers. The data generated by a traffic signal is used by maintenance engineers to assess its health, without actually visiting the signal. However, current practices are labor intensive.

The aim of our project was to demonstrate that automatic analysis techniques to process this data and detect system faults, could be developed and incorporated in a prototype software system. The primary benefit offered by such a software assistant would be a substantial reduction in the time needed to process the data generated by traffic signals. Our analysis techniques are based on the assumption that faults in the system will disrupt traffic flow. Conversely, by observing traffic flow one will be able to detect faults. We combine traffic flow information, currently not used for maintenance, with the maintenance data already generated by traffic signals for automated fault detection. To detect the presence of faults, our techniques compare measured traffic flow at adjacent signals over time.

We developed and implemented a prototype system that was tested on T.H. 13 in the Metro. We demonstrated that normal traffic flow followed established "steady-state" patterns. We also demonstrated that our system was able to flag and detect three faults: a detector fault, a flashing red fault, and a pedestrian push-button fault. Two of the three were artificially injected into the system. The third, the detector fault, was detected by observing data gathered during the test period.

Our initial results indicate that traffic flow data can be successfully used to assist in remote maintenance and sharply reduce the time needed to process data. Relative to the time required for manual data processing, the time required by our system is negligible.

# Maintaining the Traffic Control System

## APPENDIX ANALYSIS OF TRACONEX CONTROL SYSTEM

### 1. Introduction

In this document, we review the tasks accomplished in the second phase of the project titled, "Maintaining the Traffic Control System." We list the tasks outlined in the initial proposal and discuss the results achieved with each.

### 2. Traconex Control System

We had achieved reasonable success in phase 1 at detecting faults in signals manufactured by Econolite Corporation. The Metro region also contains a substantial number of signals manufactured by Traconex Corporation. We intended to extend our fault detection techniques to Traconex signals. Two tasks of the project involved Traconex. In the first, we planned to develop detection techniques for Traconex signals. In the second, we planned to integrate the Traconex and Econolite monitoring systems into a single system.

Our fault detection techniques in Econolite signals depended on an ability to reconfigure the system electronically from the control center. Upon investigation, we discovered that all the Traconex signals are configured very differently from Econolite signals. The most important distinction is that in Traconex signals detectors are hardwired to the central controller. The detector configuration cannot be controlled electronically.

To detect faults in detectors, we use multiple detector configurations to measure various traffic flow patterns. Faults are detected by identifying inconsistencies in these traffic flow patterns. Each traffic flow pattern requires a specific detector configuration. Fault detection capability is degraded if one or more detectors cannot be configured as required by a pattern. Usually, the detector configuration required for fault detection is very different from that used during normal operation. Intuitively, this may be understood as follows. During normal operation, signals are configured to sample the traffic uniformly through the system. In contrast, our analysis requires complete information on traffic flow in one pattern. Since the number of detectors that can be monitored is limited, using these configurations implies that other traffic in the system is not monitored. Readers are referred to the Phase 1 report for more details.

Because detectors are hardwired, their configuration cannot be changed electronically. Because their configuration cannot be changed, the only flow information available was that from hardwired detectors. As mentioned above, this information is usually inadequate for any fault detection analysis. In summary, the structure of the Traconex systems prevented us from extending our fault detection techniques to them.

Because we could not develop fault detection techniques, the second task related to Traconex systems could also not be performed. In the absence of an automated system for Traconex signals, the systems for Traconex and Econolite could not be integrated. Because this task could not be performed, in the absence of other direction, we invested additional effort in the remaining tasks.

### 3. Increasing Analysis Automation

At the end of the first phase, our results indicated that the methods developed could be very effective at detecting various types of faults and at reducing the processing load on the maintenance engineer. However, the prototype system converted data from several formats and systems. Hence, it required substantial manual intervention to be used.

We made several significant improvements to the tool to decrease the degree of required manual intervention. Each of the improvements is reviewed briefly:

- *Stored configuration:* Recall that our algorithms analyze the data in several traffic configurations. We incorporated the ability to read the configurations from a file and/or to store them in a file once they had been entered. This eliminated a significant limitation in the prototype tool. It also made possible the automatic creation of configuration files, if the DoT chose to adopt our tool.
- *Automatic calibration:* Our analysis algorithm requires a definition of “normal” traffic flow patterns to detect the presence of faults. This definition is performed in a calibration step. We enabled the automatic calibration of data, using limited user input. For different periods of the year, to accommodate shifting traffic flow, the tool could be calibrated with different data sets with a straightforward process.
- *Automatic analysis:* We substantially improved the analysis algorithm used in the tool. The improvements were designed to enable complete automation if the system were to be adopted by MnDoT. Our goal was to demonstrate that it was possible to execute virtually the entire analysis automatically. in the following ways:
  1. Combined historical and geographical analysis into a single step. The user need only identify the period over which data was to be analyzed. The algorithm would automatically extract and analyze the relevant data.
  2. Serially analyzed multiple configurations without additional user input. Thus, a user would not have to manually step through the various possibilities each time the tool was invoked. The tool can extract the information required from the configuration file.
  3. Correlated event report information with the information extracted from analysis. The tool consolidated event reports presented by the signal systems. As mentioned in the phase 1 report, signal systems tend to generate a large number of spurious reports. Our algorithm looked for correlation between the flow anomalies identified from detector information and items in the event report. Any correlation was used as an indicator of the existence of a real fault.

4. Incorporated limited diagnostic potential, that is an ability to analyze the type of fault. We used information provided by MnDoT personnel to identify sequences in event report information that corresponded to known failure causes. For example, a large number of coordination errors could possibly indicate a stuck pushbutton.

#### 4. Automated Data Entry

We increased the degree of automation in the entry of system data. Some of the improvements were reviewed in Section 3. As mentioned before, the goal of our efforts was to show that the potential existed for such a system to be configured and operated automatically with very limited manual intervention. The improvements made are:

- *File-based operation:* Our tool requires information on the geographic and electronic configuration of the system to be analyzed. The information required includes the number of signal controllers, their relative position and the detectors monitored by each of these controllers. If this system were to be deployed on a large scale, the amount of data entry required would be a significant obstacle to deployment. However, most of the information required is already present in electronic form – in the traffic signal systems themselves. We have redesigned the system such that it operates exclusively on file input and output. This includes system configuration, system thresholds, calibration information and traffic data input. All of these files are in fixed formats. Currently, the user creates many of these files. However, if needed, many of these files can be created automatically from existing electronic databases. This process will require permission from the manufacturer and access to their internal software code. For example, we have already used information from the manufacturer to automatically extract detector and event report data.
- *Programmable operation:* Virtually every aspect of system operation is programmable. Example of programmable options include, the number of controllers in the system, the number of detectors in the controller, the number of detectors in each configuration, the data to be used for calibration, the type of analysis to be performed and the duration of the analysis among others. This significantly increases the flexibility of the system. Secondly, when combined with file input and output, it may decrease the degree of difficulty in deployment.
- *System configuration:* As described above, we developed file formats with which the system structure and analysis configurations could be described. In the current “stand-alone” format, this feature permits users to define a system once and use it repeatedly.
- *Data extraction:* The algorithm requires data from Econolite systems. We simplified considerably the process of extracting and transferring data into our system. If our system is resident on the same computer as is the Econolite system this data extraction can be automated. To further improve analysis, the system can analyze data for up to one year.

## 5. Improved User Interface

Based on a request from our DoT contacts, we made several improvements to the analysis tool. We believe these improvements are well beyond those envisioned in the original proposal. Together, these improvements make the tool very easy to use. We believe the tool can be used with almost no technical training. The improvements we made include the following:

- *Extensive help menu:* The tool now incorporates a very detailed help menu covering all aspects of system operation. The items covered include, detector data extraction, event report extraction, system calibration, data analysis and data output. For example, the help menu provides a step-by-step guide to extracting event report data by transforming it from a proprietary Econolite format to an Ascii format. Similarly, the help menu guides a user through a typical system set-up and analysis process. That is, identifying the structure, configurations for analysis and calibration.
- *Data output:* We have provided a data output interface such that data can be output in a format that can be used by a charting tool. This will enable a user to follow-up and visually analyze data that has been flagged by the analysis program. In practice, we have found this to be a very useful tool.

## 6. Testing

Concurrent with the development of the algorithms, we continued to test the system on the target highway, discussed in the final report for Phase 1. We did not notice any anomalous behavior during the period of the test. Unfortunately, we lost the data accumulated during the test period. We were also asked to terminate testing, by our technical contact, in July 1997.

## 7. Related Activities

In addition to developing the system, we performed the following activities to publicize our system with a wider audience. We presented two technical papers, at the 1996 ITS Symposium and the 1997 CTS Technical conference. We delivered copies of the software program and sources code to our technical contacts in MnDoT and the ESS section. We demonstrated the use of our software program, to various MnDoT personnel, in 1997 and in 1998.

## 8. Conclusion

We have reviewed the various tasks performed during this project. One task could not be performed because of unexpected technical results. We invested additional effort in other tasks. Our efforts improved the analysis algorithm, increased the degree of automation in data entry and improved the user interface. We also attempted to publicize our system to various audiences. Our efforts improved the tool, made it easier to use and decreased the cost of any eventual deployment.

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