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Development and Testing of Operational Incident Detection Algorithms: Executive Summary

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FOREWORD

This report describes the development of operational surveillance data processing algorithms and software for application to urban freeway systems, conforming to a framework in which data processing is performed in stages: sensor malfunction detection, data repair, calibration, qualitative modeling of traffic conditions, and, finally, discrimination of incidents from recurrent congestion. Development and testing used real data obtained from freeway systems in Oakland, CA, San Diego, CA and the Twin Cities in Minnesota. Statistical pattern recognition techniques, including optimal decisions trees and neural nets were used. The algorithms and software produced are designed for integration into real-time traffic management systems. This Executive Summary provides an overview of these developments.

This document is intended for local traffic management authorities responsible for operating and/or planning freeway incident and response capabilities, at locations where such capabilities are in place or are being considered for deployment.

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16. Abstract New operational surveillance data processing algorithms and software for application to urban freeway systems have been developed and tested, conforming to a framework in which data processing is performed in stages: sensor malfunction detection, data repair, calibration, qualitative modeling of traffic conditions, and, finally, discrimination of incidents from recurrent congestion. Development and testing used real data obtained from freeway systems in Oakland, CA and the Twin Cities in Minnesota. Statistical pattern recognition techniques, including optimal decisions trees and neural nets were used. This first volume presents an overview of the study highlighting the research methodology, major accomplishments, and conclusions, and recommendations for future research. The other volumes of this report are: Modification and Application of FRESIM for Modeling Congestion and Incident Scenarios Development and Testing of Operational Incident Detection Algorithms: Software Documentation Development and Testing of Operational Incident Detection Algorithms: Technical Report In addition, this report is accompanied by a CD-ROM containing the source code documented, and various data bases developed and used in this project.					
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Development and Testing of Operational Incident Detection Algorithms: Executive Summary

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I. THE INCIDENT DETECTION ISSUES PROJECT

Responding to the increasing need to improve means for managing nonrecurrent congestion, the Ball Aerospace & Technology Corporation was contracted by the Federal Highway Administration to develop and evaluate incident detection algorithms for use in Intelligent Vehicle Highway Systems (IVHS), and to develop a procedure to report and quantify the operational effects of freeway incidents, in a study entitled "Incident Detection Issues."

This study had three objectives:

1. Examine and evaluate the entire issue of incident detection and verification, existing incident detection systems, related surveillance requirements for traffic control systems, and determine the deficiencies in current incident detection and surveillance practices.
2. Develop and field verify three approaches to freeway incident detection which overcome the deficiencies identified in Objective 1.
3. Develop a methodology for the uniform measurement and reporting of incidents, and the necessary data base of incident frequencies, types, duration, capacity reduction, and other data needed to predict the occurrence and impacts of incidents on freeways,

The study was conducted over the period April 1993 through September 1997. The third objective was addressed by Ball and its subcontractor, California Polytechnic State University at San Luis Obispo in work that concluded in April of 1995. The remaining work was conducted by Ball and its subcontractor, the University of Maryland.

Work on the third objective is reported in a separate pair of documents identified in the next section. This Executive Summary and the other volumes of this final report are limited to the remainder of the project work, that is, the development and testing of approaches that support automatic incident detection.

II. PROJECT DOCUMENTS

This project produced a series of interim technical reports. several papers presented at conferences, a final report pertaining to the assessment of impacts of incidents, and a final report pertaining to the development and testing of incident detection algorithms.

Interim Project Reports

This project produced a series of interim technical reports, as follows:

Payne, H. J., "Technical Report Incident Detection Issues: Task A.2," BSEO Report R-O 15-93.

Chang, Gang-Len, Payne, H. J., and Ritchie, S. G., "Incident Detection Issues Task A Report: Automatic Freeway Incident Detection--A State of the Art Review," BSEO Report R-024-93.

Payne, H. J. , "Analysis of Incident Detection and Incident Management Practices--Working Paper," BSEO Report R-030-93.

Payne, H. J.. "Incident Detection Issues Technical Memo: Description of San Antonio Traffic Management System," BSEO Report R-006-94.

Chang, Gang-Len, Yan Lin Li. and Payne, H. J.. "Incident Detection Issues Task B Report: Evaluation Plan." BSEO Report R-007-94.

Erbacher. J., "Technical Memorandum: Incident Detection Issues Hardware Specifications and Software Recommendations." BSEO Report R-009-94.

Payne, H. J. and Thompson, S. M. "Incident Detection Issues: A Technical Approach to Developing Advanced Incident Detection Algorithms," BSEO Report R-O 1 0-94.

Payne. H. J., "Issues in Developing and Testing Incident Detection Algorithms," BSEO Report R-01 1-94.

Sullivan, E. and Payne, H. J., "Incident Detection Issues Task I Interim Report," BSEO Report R-O 17-94.

Thompson, S. M. and Payne, H. J., "Incident Detection Issues Task C Report: Functional Requirements Specification," BSEO Report R-032-94.

Thompson, S. M. and Payne, H. J., "Incident Detection Issues Technical Memo: Evaluation of the Operational Algorithm," BSEO Report R-033-94.

Payne, H. J., "Incident Detection Issues Technical Memo: Task G Field Tests," BSEO Report R-035-94.

Boaz, R. B., "Incident Detection Issues Task E. 1 Report: Real-Time Incident Detection Environment (RIDE) System Specification," BSEO Report R-010-95.

Papers Presented at Conferences

Papers were presented at conferences, as follows:

Payne, H. J. and Thompson, S. M.. “Development and Testing of Incident Detection Algorithms: A Status Report on the Ongoing FHWA-Sponsored Project,” presented at the 1996 Transportation Research Board Meeting, Washington D.C.

Payne, H. J., Thompson, S. M. and Chang, Gang-Len, “Calibration of FRESIM to Achieve Desired Capacities,” presented at the 1997 Transportation Research Board Meeting, Washington D.C.

Payne, H. J. and Thompson, S. M., “The I-880 Database: Malfunction Detection and Data Repair for Induction Loop Sensors,” presented at the 1997 Transportation Research Board Meeting, Washington D.C.

Payne, H. J. and Thompson, S. M.. “Identification and Tracking of Traffic Queues,” submitted for presentation at the 1998 Transportation Research Board Meeting, Washington D.C.

Payne, H. J. and Thompson, S. M., “Development and Testing of Operational Incident Detection Algorithms Based on Classification of Traffic Queues.” submitted for presentation at the 1998 Transportation Research Board Meeting, Washington D.C.

Final Report Documents Pertaining to the Assessment of Impacts of Incidents

This project produced a final report pertaining to the assessment of impacts of incidents. in documents as follows:

Sullivan, Ed and Payne, H. J. (1994). “Incident Detection Issues: Final Report for Tasks H-J,” prepared for the Federal Highway Administration, Washington D.C.

Sullivan, E. and Champion, D. (1995). “IMPACT 1.0: A Model for the Estimation of Incident Impacts on Freeways,” prepared for the Federal Highway Administration, Washington D.C.

Final Report Documents Pertaining to the Development and Testing of Operational Incident Detection Algorithms

This project produced a final report pertaining to the development; and testing of operational incident detection algorithms, in documents as follows:

Payne, H. J., “Development and Testing of Operational Incident Detection Algorithms: Executive Summary,” BSEO Report R-010-97.

Chang, G. L., Ge, W., Payne, H. J., and Smith, P., "Modification and Application of FRESIM for Modelling Congestion and Incident Scenarios," BSEO Report R-008-97.

Payne, H. J. and Thompson, S. M., "Development and Testing of Operational Incident Detection Algorithms: Technical Report." BSEO Report R-009-97.

Boaz, R. and Harlow, C. "Development and Testing of Operational Incident Detection Algorithms: Software Documentation." BSEO Report R-O I 1-97.

CD-ROM containing source code, data bases and various supplemental files.

III HIGHLIGHTS OF PROJECT RESULTS

This Incident Detection Issues project was successful in producing new, operationally useful loop surveillance data processing techniques that collectively support automated incident detection. Our discussion of these results begins with attention to state-of-the-art at the outset of project work, and then presents project results.

Background

Freeway congestion due to the occurrence of incidents is a major cause of traffic delays in the United States and around the world. The Federal Highway Administration reports that incident-related delays account for approximately 60% of all urban freeway delay in the United States'. Mitigation of such delays through rapid and reliable incident detection is clearly a vital traffic management objective.

We have found that the methods used to perform incident detection vary significantly in both structure and effectiveness in urban locations across the country. In most instances, agencies with vehicles patrolling the freeways will detect incidents by discovery. Several locations also make use of cellular phone calls from freeway motorists to identify incidents. Conversely, relatively few sites perform incident detection based on electronic surveillance data, and such techniques are frequently employed only to detect very severe incidents. Nevertheless, automated surveillance-based incident detection systems have demonstrated significant abilities and hold the potential to greatly facilitate rapid incident detection and the subsequent deployment of appropriate response forces.

Since the mid- 1970's, various surveillance-based incident detection algorithms have been developed. Unfortunately, the algorithms developed to date have met with only limited operational success, and it is clear that improved algorithms are needed to make surveillance-based incident detection technology operationally effective. Specifically, existing algorithms have been largely unable to maintain the high degree of reliability required in practice (e.g., high detection rate and low false alarm rate). Despite this limited success, several proposed algorithms clearly warrant further development and evaluation.

¹Lindley, J A. (1987). "Urban Freeway Congestion: Quantification of the Problem and Effectiveness of Potential Solutions"

The most well-known and widely-used incident detection algorithm is the California Algorithm(s)². This class of algorithm detects Incidents based on comparisons of traffic measurements from adjacent detector stations. These stations are typically comprised of induction loops measuring traffic volume (vehicles per hour) and occupancy (percentage of time that a vehicle is directly above the station) at 30-second intervals. The underlying principle is that a capacity-reducing incident causes upstream occupancy to increase and downstream occupancy to decrease. Accordingly, an incident is declared when the difference between upstream and downstream occupancy readings is sufficiently high. The California Algorithm(s) also make use of “persistence tests”, which prevent temporary traffic fluctuations from being misinterpreted as incidents.

Another well-known class of algorithm is the McMaster Algorithm(s)². This class of algorithm detects incidents in two distinct phases: (1) detect the existence of traffic congestion, and (2) determine the cause of congestion. For any given detector station, congestion is detected when occupancy and volume readings rise above established thresholds. The cause of congestion is then determined based on readings from the adjacent downstream station. In essence, the cause of congestion is deemed to be a capacity-reducing incident if the volume and occupancy readings from the downstream station are sufficiently low. Otherwise, the congestion is deemed to be of the “recurrent” variety, which arises when traffic demand exceeds freeway capacity.

In recent years, several new methods of performing surveillance-based incident detection have been proposed. The most promising of these include algorithms which utilize neural network technology and algorithms which are based on models of traffic dynamics.

As one of the principle applications of neural network technology is to pattern recognition problems, they hold considerable potential for recognizing and classifying spatial and temporal patterns in traffic data, and therefore for detecting Incidents. Various studies have been conducted which support the feasibility of this approach.

Algorithms which are based on models of traffic dynamics detect incidents by explicitly modeling unrestricted traffic flow on freeway sections of interest. These models are used as the basis of a data processing technique that produces traffic state estimates, and their

²Payne, H. J., Helfenbein, E. D., and Knobel, H. C. (1976). “Development and Testing of Incident Detection Algorithms. Volume 2 Research Methodology and Detailing Results”

deviations from traffic measurements. Incidents can then be detected by classifying filter state estimates and these deviations, based on the principle that large deviations indicate the model's assumption of incident-free traffic conditions is incorrect,

The thrust of this study was to use the algorithm types described above as the basis for developing improved algorithms. Aspects of each of these approaches were incorporated into a comprehensive algorithm architecture and systematic means for development were applied. New opportunities were made possible by today's more powerful computers, which are capable of supporting sophisticated algorithms. removing several of the limitations imposed on previous efforts.

Highlights of Approach and Findings

This project produced new algorithms and software for loop surveillance data processing which offer significant improvement for operational freeway surveillance systems. Much of the improvement is derived from breaking the development into a sequence of processing steps. with attention to important operational issues.

Framework for Surveillance Data Processing

An important aspect of the project work was the development of a framework for operational quality incident detection for urban freeways in which a process of surveillance data processing is performed in stages: sensor malfunction detection. data repair. calibration. qualitative modeling of traffic conditions and. finally, discrimination of incidents from recurrent congestion. (See Figure III-I .) This framework borrows an important concept that is a part of the McMaster algorithm: distinct steps for congestion identification and discrimination of incidents.

Each stage has distinct objectives and needs to reflect the specific characteristics of the surveillance system, including the particular sensors and their deployment. While our work has been restricted to the most prevalent sensor, the induction loop, this framework should be effective for other sensors as well, while the specific algorithms will need to be specific to those sensors and how they are deployed. Our work has demonstrated the crucial role played by each of these steps in ultimately arriving at an operationally useful

capability for incident detection. At the same time, each of these steps has great operational utility in and of themselves.

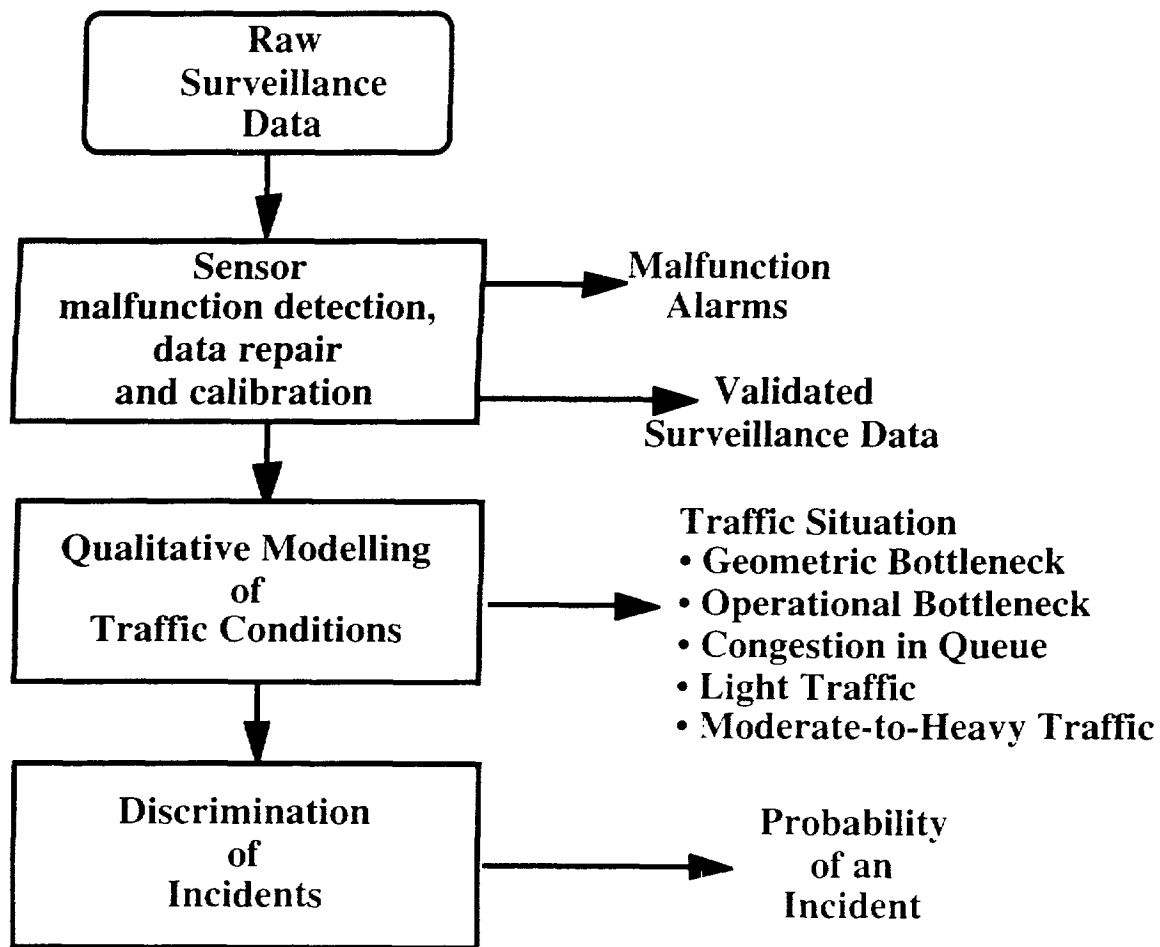


Figure III-1. Project work created algorithms within a framework for operational surveillance data processing, with incident detection as the final stage.

Preprocessing Stages: Malfunction Detection, Data Repair and Calibration

All induction-loop sensors are subject to malfunction, and such malfunctions can dramatically and adversely affect subsequent processing of the sensor data. As such, real-time detection of sensor malfunctions is a critical issue for many applications. Also of interest is the ability to “repair” faulty sensor data when possible by estimating traffic measurements for malfunctioning sensors.

In this project the study of sensor malfunctions was motivated by the desire to prepare data for processing by incident detection algorithms. A significant problem encountered in previous incident detection efforts was that faulty measurement data frequently induced false alarms and significantly reduced the performance of the resultant algorithms.

Project work first exploited a data base obtained from the I-880 freeway in Oakland, CA; subsequent work used data for the entire Twin Cities freeway system. We found that loops fail frequently (typically, ten per cent failing at any time), even in well-maintained systems. Algorithms were developed that successfully detect a variety of malfunction types, ranging from the fairly obvious (e.g., missing data) to the more subtle (e.g., suspicious speeds).

Algorithms for “repairing” faulty sensor data were also addressed. These algorithms rely on estimating the distribution of traffic across mainline lanes for full-count stations and then scaling the distribution according to current traffic levels. The data repair algorithms are suitable for applications that do not rely on the absolute accuracy of individual measurement data, such as traffic monitoring. Applications that require this kind of accuracy, such as automatic incident detection, may be better served by simply screening faulty data from subsequent processing.

Fairly simple but comprehensive techniques were also employed to calibrate single loops to more reliably produce speed measurements -- an important step, as speed was found useful in subsequent processing steps.

Queue Tracking

Methods to identify and track queues were yet another set of important processing steps produced in this project. They are both operationally useful on their own and a crucial part of the preprocessing sequence leading up to the discrimination of incidents. Our work extends the method contained in the McMaster algorithm: in addition to identifying heads of queue, our work includes tracking of “congestion events,” extended areas that evolve in time and contain the region of queuing. Tracking greatly reduces the number of events that need to be classified.

The results of queue tracking are readily portrayed in a data visualization technique that portrays the freeway system schematically, as illustrated in Figure III-2. The roadway is shown with each direction separately depicted. Zones, or regions bounded by mainline

stations, are color-coded according to the results of data processing on data for that zone. In Figure III-2, congestion is depicted through the simple color coding scheme that uses red for the head of queue and the in queue zones, uses yellow for the tail of the queue, and uses green for all other zones.

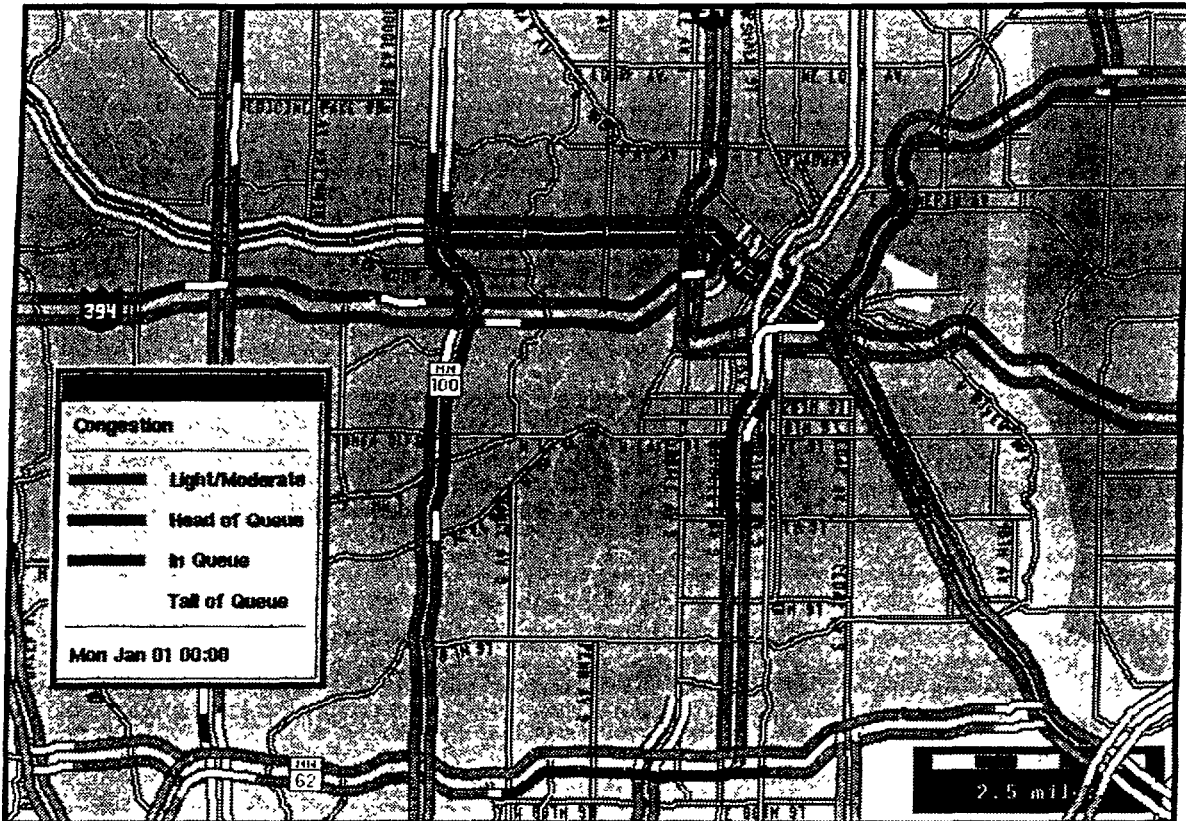


Figure 111-2. The surveillance data processing steps through queue detection and tracking, illustrated here for the Twin Cities Freeway System, were crucial precursors to the application of incident detection algorithms.

Data Used for Algorithm Development

Algorithm development and validation was based entirely on real data. We constructed a capability for acquiring real data and attaching labels of incident or incident-free conditions, and successfully used it with the Twin Cities freeway system to obtain a very substantial body of useful data for both training and evaluation. Figure III-2 above illustrates the scope of this data acquisition -- the entire Twin Cities freeway system.

The real data sets are qualitatively different from previous such data sets, in their comprehensiveness in space (covering 300 miles of freeway) and time (covers more than two weeks, morning and peak periods), and the quality of the labelling (we could positively label congestion events using a comprehensive CCTV system). We had sufficient data to create separate training and evaluation data sets. The evaluation data set covered the entire Twin Cities freeway system for a week for both peak periods, and therefore directly measured the operational effectiveness of the algorithms.

AU of this data in raw and processed form, including labelling of incident-induced and recurrent congestion events, has been made available on CD-ROM as a part on this final report.

We also developed extensive simulations of Minneapolis and San Diego freeway traffic using FRESIM. Our intent was to provide a basis for the controlled development of labelled data sets that could be used in developing incident detection algorithms. We did make very considerable progress, generating simulations for about 50 directional miles for each freeway system for fifteen hours that were reasonably representative of daily, congested traffic, but we were not able to complete our exploration and refinement of FRESIM in an attempt to realistically model incidents. Based on our detailed examination of real data, the challenge in simulating incidents is very great, and more work needs to be done.

All of our work on FRESIM is documented in full as one of the volumes of this final report. The report presents schematics that completely document the geometric coding. Complete FRESIM input files are included with the final report CD-ROM.

Development and Testing of Incident Detection Algorithms

Development focused on discriminating incidents as the cause of new congestion events. Operationally, the most important situations regarding the detection of incidents are congestion events. Incidents in light traffic which do not create congestion (immediately) may be important as well, but we did not address these conditions.

Algorithms were developed that produced a probabilistic statement of the likelihood of an incident. Instead of declaring that an incident was definitely present or definitely not

present, each algorithm produced an estimate of the probability of the new congestion event being caused by an incident.

A new Bayesian approach was developed. Our work using a decision-tree technique identified two features as good discriminators: downstream volume and upstream-downstream speed difference. This result is similar to the second aspect of the McMaster algorithm in which incident discrimination is based on downstream volume and occupancy. Generally, we found that incidents had a tendency to produce lower downstream volumes, lower downstream occupancies, and greater differences in upstream and downstream speeds. The simplicity of this result and our desire to provide a probabilistic statement of the likelihood of an incident led us to create a new technique that estimated the a posteriori probability of an incident given the surveillance measurements.

Several neural-net-based algorithms were developed. Guided by previous work by others we developed several variations of neural nets.

Evaluations included the Bayesian, neural net and California-type algorithms. Evaluations were performed using the evaluation data set that entailed all the peak period traffic for a week in the Twin Cities freeway system. The incident detection algorithms we investigated performed similarly, as illustrated in Figure III-3, where we show the tradeoff that is available through selection of an algorithm threshold between the detection rate (fraction of incidents that are detected) and the operational detection rate (fraction of “alarms” that prove to be incidents). There was some indication (not statistically validated) that the neural net approach produced somewhat better results. As can be seen from the figure, these algorithms produced only modest ability to discriminate incidents as the cause of new congestion events, with the operational detection rate being in the range of 20 to 40 per cent.

Most of the benefit to incident detection actually comes from the series of preprocessing steps, particularly the queue detection and tracking step. These steps serve to eliminate false alarms from a variety of sources, and limit the attention of the incident detection algorithms and system operators to new congestion events. These benefits are very substantial, and combined with the incident discrimination algorithms, produce operationally useful results.

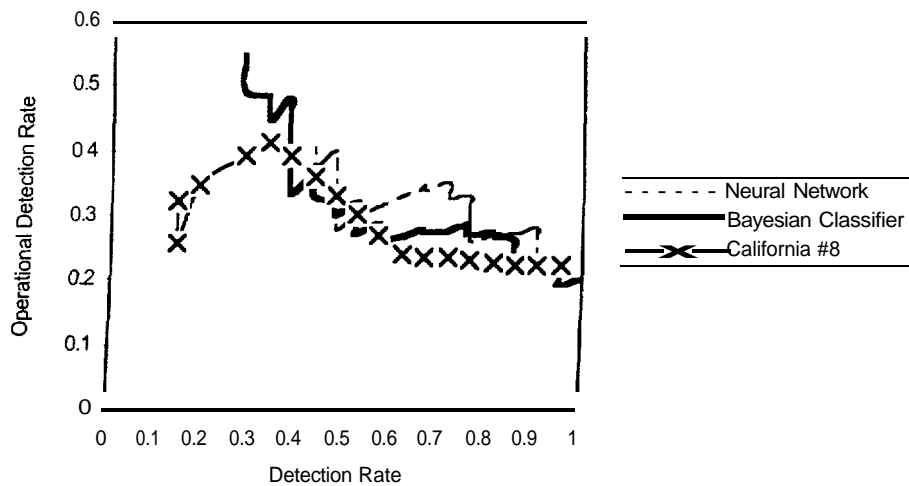


Figure III-3. Several incident detection algorithms produced similar modest benefits in discriminating incident-induced congestion from recurrent congestion.

Available Software

This project produced a substantial body of software, which we termed the Real-Time Incident Detection Environment (RIDE). RIDE incorporates all of the algorithms that were produced, and provides interfaces to both real data (from Oakland, Minneapolis and San Diego) and simulated data (from FRESIM). This software is fully documented in one of the volumes on the final report, and delivered as source code on a CD-ROM.

Implications for Operational Use and Performance

The framework and individual surveillance data processing algorithms that have been developed in this project have immediate use in ATMS and ATIS systems. The preprocessing steps of malfunction detection, data repair and calibration are necessary precursors to the effective use of surveillance data in many applications -- certainly incident detection, as we have described here, but also in traveller information and ramp metering. Much of the processing software developed is in current use as a part of traveller information systems in Minneapolis and San Diego.

Existing incident detection algorithms used where congestion is prevalent are not operationally useful due to the very large false alarm rates. The preprocessing steps

developed in this project, and the associated algorithms that discriminate incidents where congestion is found. provide an operationally useful capability.

In operational use, these algorithms locate and track congestion events. As each new such event is identified, the incident discrimination algorithm presents the estimated probability that the new event is in fact caused by an incident. In a typical case, the value of this probability might range from 5% to 80%, so that important information is provided that draws the attention of systems operators where there is strong evidence of an incident, e.g., when the probability is estimated to be 40% or so, but suggests that the congestion is most likely recurrent, when this probability is low. The result is that fewer events need to be considered, and in those cases, priorities based on the probability can be assigned until an incident is confirmed, or the event is determined not to be an incident.

IV. RECOMMENDATIONS

Recommendations are offered here for further research, and for measures designed to foster operational use.

Further Research

FRESIM deserves additional attention to complete work necessary in making it suitable as the basis for further research on incident detection algorithms. Very considerable progress was made, generating simulations for about 50 directional miles for both the Minneapolis and San Diego area freeway systems for fifteen hours that were reasonably representative of daily, congested traffic. Improved flexibility in modeling, and improved modeling of congestion (both recurrent and non-recurrent) is needed.

The best opportunity for improvements in incident detection performance will come with better modeling generally, and in particular capturing recurrent congestion. There are at least two approaches that could be considered:

Qualitative modeling using statistical approaches: With this approach, traffic zones are labelled over an extended period of time, to form a data base for statistical analysis that would lead to a characterization of recurrent congestion. This approach would require a large effort to gather and label data, and any such effort would need to be repeated fairly often as the traffic conditions evolve from year to year.

Model-based approaches: With this approach, a macroscopic model would be created for the freeway system which would capture gross characteristics of each freeway segment, e.g., number of lanes, and local capacity. Then recurrent congestion would in principle be predicted by application of the model using that day's surveillance data. The algorithmic basis of this approach is described in project documents, but we were not able to complete our work by applying this method to real data.

In either case, incidents would stand out as unexpected breakdowns or onset of congestion.

The simplicity of both the Bayesian approach and the California algorithms and their dependence on intuitively meaningful features suggest that these algorithms should transfer well, from the environment in the Twin Cities that was used for development, to other venues. The fact that training was done on such a large data set spanning a large freeway

system with a great deal of variation in geometrics and traffic levels suggests that both the Bayesian and neural-net techniques should transfer well. It will be important to test the ability of these algorithms to perform usefully elsewhere.

The framework we have developed is believed to be useful where surveillance systems use alternative forms of surveillance devices, including radar and video cameras. New algorithms for malfunction detection need to be developed that are specific to the type of sensor. Each of the following steps in the framework is largely independent of the specific type of point sensor, but further research is certainly warranted to test and improve the algorithms that have been developed.

Development of Operational Software and Implementation

The malfunction detection algorithms that have been developed can be used in a fairly direct manner in operational systems, as they are mostly phrased in terms of individual loops and mainline stations. Algorithms for data repair and calibration of single loops to produce reasonably accurate measures of speed in an operational form need much more work, mostly to reflect the operational features of specific systems. For example, in calibration, the key is to make regular independent measurements of speed with enough spatial granularity to distinguish actual variations in speeds as they occur over a freeway system. One way to do this is to install double loops or radar sensors at intervals to produce standard speed measurements, and associate each single-loop station with a standard speed measurement. At the extreme, single loops get replaced everywhere by double loops or another speed measurement technique.

The software delivered with this project is to be characterized as functional prototype software. In an operational environment, re-implementation of the basic algorithms would be required and will entail a substantial software effort to model the roadway and its relationship to surveillance data. The project software documentation provides one model for how to do this: it uses a roadway-object orientation in the C++ language to organize all data and processing.

As these project results are absorbed by practitioners and systems builders, the project prototype software can be used directly, since it has been developed to work in a stand-alone fashion using modular interfaces to real-time surveillance data. This use can be

valuable in familiarizing system operators with the new capabilities, and in fashioning the specific requirements for an integrated implementation.