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16. Abstract

Vehicle detection through machine vision is one of the most promising advanced technologies available today for dealing with the problem of urban traffic congestion. In this project an existing Wide Area Detection System (WADS) was improved for performing detection under all weather, traffic, and artifact conditions (e.g. shadows, reflections, lightning, etc. As a result of this and other related research efforts by the same team, a real-time (instead of the initially envisioned off-line) multispot breadboard WADS system was developed, installed, tested, and demonstrated in several real-life situations. The system can simultaneously detect traffic at multiple points within the field of the camera's view and emulates loop detectors. The test results to this point suggest high accuracy levels, comparable to loop detectors, while speed measurement appears to be more accurate than loops. Live demonstrations and off-line presentations generated the enthusiasm and support of practicing engineers and public officials. They also suggest that the WADS system developed in this project is the most advanced one available today. Despite this, further work remains to be done prior to production. This includes extensive field testing and validation as well as implementation of applications possibly through demonstration projects. This report describes the WADS algorithm development and testing and makes recommendations for field implementation of the technology.

17. Key Words
Detection, Image Processing, Detectors, Machine Vision, WADS

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

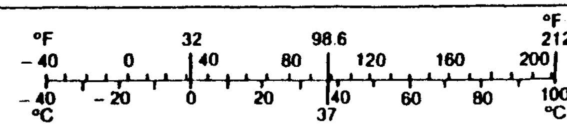
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	MASS			
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
	TEMPERATURE (exact)			
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION AND SUMMARY

Vehicle detection seems to be the weakest link in traffic surveillance and control. Although sufficient equipment is available today for detecting vehicle presence on the roadway, it essentially employs technology of the late 1950's, has limited capabilities, presents reliability problems and, more often than not, requires massive and expensive installation for reasonably traffic responsive control. The latter is particularly true in state-of-the-art surveillance and control systems, which often involve large-scale street or freeway corridor networks. With respect to reliability it is noted that most cities with mature systems in the U.S. report that 25 to 30 percent of their detectors are not functional or operating properly at any time. Furthermore, discussions with suppliers and manufacturers suggest that often loop detectors seem to be active but, in reality, are producing false or inaccurate actuations. Finally, adverse weather conditions or pavement reconstruction presents additional challenges for maintaining loop detectors, the most widely used detection device.

Perhaps the most important drawback of existing detectors is their limitation in measuring some important traffic parameters and accurately assessing traffic conditions. This is because the technology employed represents a "blind" type of detection, i.e., only the presence of vehicles over the detectors can be assessed with high accuracy. Traffic parameters such as speed, traffic composition, queue length, etc. must be derived from presence signals and require multiple detections which increases cost and exacerbates the reliability problems mentioned earlier. Furthermore, common detectors (such as loops) do not have surveillance or sufficient vehicle recognition capabilities; most importantly, they provide only one vantage point. The latter is an important drawback for traffic control since the detection points should vary with speed, volume, and control objective to allow control to be fully optimized. For example, speed can be more accurately measured if speed trap detector spacings can be made longer as the speed of traffic increases. Detectors that are movable under computer control can also be used to find the exact termination of a queue and even monitor its formation.

Despite the aforementioned problems, existing detectors (i.e., loops) cannot be casually dismissed, as they represent proven technology which will continue to serve its purpose in the foreseeable future. However, recent advances in image processing and understanding, electronic cameras, special purpose computer architectures and microprocessor technology, have made the machine vision alternative for vehicle detection attractive, economical and promising. A machine vision system for vehicle detection consists of an electronic camera overlooking a long section of the roadway. From the images received by the camera, a microprocessor or a larger computer determines vehicle presence or passage and derives other traffic parameters, preferably in real time. Vehicle detection can be obtained at specific points of the roadway while other traffic parameters can be derived by analyzing the images of the entire roadway scene. A video-based vehicle detection system is often referred to as WADS, for wide area surveillance system.

The advantages of vehicle detection through image processing are many. To begin with, a WADS system can have multitasking capabilities, i.e., while performing its basic detection functions it can simultaneously derive traffic measurements locally (using a microprocessor) or at a central location, perform surveillance functions, act as a vehicle counting and classification station, detect incidents and alert a human operator, and recognize special vehicles (ambulances, fire trucks, buses, etc.). There are, of course, other secondary tasks that a WADS system can perform including collecting and preprocessing data that can be used in conjunction with existing traffic software packages, revealing the nature of an incident by transmitting images of the scene after the incident is detected, recording data for accident analysis, and reconstruction. Finally, a WADS system can be used as an evaluation device for measuring and assessing the quality of traffic flow or for deriving measures of effectiveness for traffic studies.

A WADS system does not disturb the pavement and should, therefore, improve reliability, especially during reconstruction operations. Furthermore, it can detect traffic in a cost-effective manner by simultaneously monitoring multiple spots of the roadway within the field of the camera's view. For instance, in the feasibility study performed by the authors, it was estimated that at a typical intersection the WADS system design presented here, would save 35 percent of maintenance and 30 percent of equipment (detection) costs while reducing the person hours required for maintenance by about 70 percent.(1) The savings can be further increased if the same microprocessor also performs control functions, thereby eliminating the need for a separate controller. Furthermore, simultaneous detection at 30 to 40 points using one or multiple cameras is possible.

The flexible detection configuration of WADS, combined with its ability to extract traffic variables that cannot easily or accurately be obtained by conventional detection devices, suggests that the system should be particularly effective for automatic surveillance and control of saturated networks.

Because of these advantages, there is worldwide interest in developing a cost-effective system. Research on image processing for vehicle detection began to evolve during the mid-1970's in the U.S., Europe and Japan. Research by the contractor started in 1984.

As a result of the contractor's research efforts, a real-time multispot breadboard vehicle detection system has been developed, installed, and tested in several real situations. A video camera in the field transmits an image of a roadway scene to the user. Detector placement is accomplished interactively within minutes by placing detection lines using a mouse on a television monitor displaying the roadway scene. These lines can be placed in any desirable configuration depending on the application. Once these "pseudo-detectors" are placed, the system processes live video from the roadside camera, in order to generate presence and passage signals, and estimate speeds. From these measures the system can then derive essential traffic parameters such as volumes, headways, and occupancy. Furthermore, the system allows for visual inspection of detection results along with the actual traffic conditions for validation purposes and optimizing of detector placement. Detector placement can easily be changed as often as desired, either manually or automatically. Special algorithms for treating artifacts such as rain, snow, shadows, and pavement reflections allow the system to operate continuously on a 24-hour basis. Any ordinary video camera used for surveillance purposes can be hooked to the prototype system although solid state cameras without blooming characteristics improve the system's accuracy and effectiveness. It should be noted that unlike earlier experimental units, the WADS system presented here not only operates in real time and deals effectively with all the aforementioned artifacts, but also operates under diverse traffic conditions, from light to heavy traffic flows.

Following the initial algorithm development, testing was performed for algorithm optimization using videotaped data. Subsequently the system was installed at the freeway surveillance and control center of the Minnesota Department of Transportation in Minneapolis and tested against live data from several cameras.

The results to this point are very encouraging, suggesting potential performance beyond that of loops.

Detailed accounts of the three major tasks, that conclude the project effort are presented, in this report. Task D is related to WADS Algorithm Development, Task E to WADS Algorithm Validation, and Task F to WADS Specifications and Applications.

The report also contains summaries of the three initial project tasks, Tasks A through C, which were covered in greater depth in the interim report.[2] These tasks include WADS Hardware Design/Procurement, WADS Data Collection, and WADS Data Analysis. The report concludes with recommendations concerning further development and demonstration of the technology.

2 PROJECT OBJECTIVES AND RESULTS

The overall goal of the WADS technology development is the capability to detect vehicle presence, passage, and speed using video cameras, with accuracy sufficient for application in automated traffic surveillance and control. The primary objective of this project was to develop WADS algorithms which perform vehicle detection under all weather, traffic, and artifact conditions (e.g., shadows, reflections, etc.) and verify these algorithms on a set of data large enough to give high confidence in their operation.

This objective was to be accomplished by the completion of six major tasks, as shown in figure 1. The tasks were not completed in a strictly sequential manner. As the project proceeded, a cyclic relationship developed between the tasks which could be termed the **algorithm development life cycle.** Task results fed forward to structure efforts on subsequent tasks, as well as fed backward to control continued work in previous tasks. For example, once Task B (collection of video field data) was partially complete, Task C was initiated (analysis of video field data), in order to steer further efforts in data collection, and at the same time provide preliminary information for algorithm design.

The objective of Task A (WADS hardware design/procurement) was to identify and/or develop facilities for the collection of video field data and the development of detection algorithms and related software. For the collection of videotape data, existing traffic surveillance facilities were identified. These facilities were the Mn/DOT Traffic Management Center and similar installations of the Florida, Maryland, and Michigan DOT. For development support, a PC-based image processing facility was assembled and engineered especially for the development of WADS

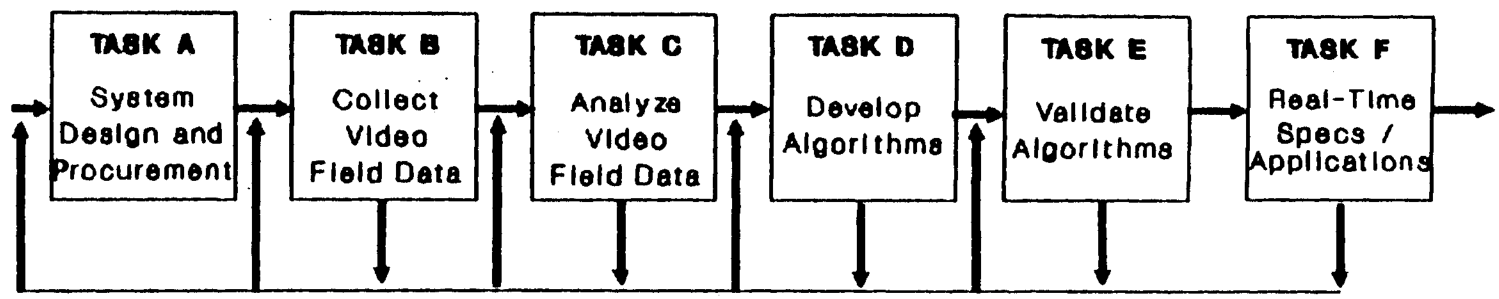


Figure 1. Relationship between project tasks.

algorithms and software. The main components of this facility are an IBM PC-AT compatible microcomputer and an optical video disc player. Embedded in the PC-AT are a real-time video digitizer connected to the video disc player, and a software module providing a software emulation of the real-time image preprocessing circuit board developed under a different contract.

The objective of Task B, WADS Data Collection, was to collect videotaped data of traffic patterns and vehicles under different weather conditions at various times of the day (day, night, dawn, dusk) along with many of the artifact conditions which have caused errors in the previous WADS algorithms. When this data was collected, it augmented the existing database with conditions that were not covered in previous data-collection efforts performed by the contractor. Data collection was done for both freeway and intersection locations with the majority taken from camera locations in freeway traffic surveillance systems. For this effort a camera was installed at the Mn/DOT Traffic Management Center that could be dedicated to intersection surveillance. Once Task B was complete, videotape data continued to be collected as new or seldom encountered conditions that cause reduced detection performance were encountered. This allowed the continuous increase in the breadth and scope of imagery which the system has been exposed. Once again, the processing of this expanded library of videotapes has been made feasible by the advent of the hardware formatter, a real-time image-preprocessing board.

In Task C, WADS Data Analysis, the objective was to analyze the collected video data and select a representative set of difficult video sequences on which to base the development and evaluation of WADS algorithms. Sequences from this collected data were manually screened for desired conditions and transferred to a 30-minute optical video disc. This optical disc, in conjunction with an existing 14-minute optical video disc, formed the initial database for algorithm development and evaluation.

The objective of Task D, WADS Algorithm Development, was to improve the performance and reliability of existing WADS algorithms under unfavorable artifact conditions, such as shadows, headlight reflections, rain and snow. Analysis of various detector configurations was conducted, as to their potential for extraction of information that would aid in the discrimination of vehicles from artifacts. This in turn led to an investigation of potential statistical features that could be derived from the detector signatures. Finally, a state machine based on sequential decision theory was constructed in order to fully implement the necessary adaptive detection approach. The output of this state machine is the vehicle presence, passage, and speed that can be used to derive other traffic parameters. In addition to the aforementioned artifacts, the artifact of congestion, a potential problem for an adaptive technique, was dealt with.

The algorithms were developed off-line, by setting up and running batch files through V3COM, designed to facilitate the quick prototyping of algorithmic approaches, with high-level support for the manipulation and transformation of signal and image data stored in a device independent file structure. When finalized, these algorithms were converted to an efficient "C" implementation under a different contract. This allowed for quick visual inspection of performance, and greatly aided the demonstrability of the WADS technology.

The goal of Task E (WADS Algorithm Validation) was to validate the performance of the newly improved WADS algorithms by running them on approximately 5,000 frames of video data selected in Task C. The output was to be automatically scored by comparison with a manually entered database of vehicle presence.

This was accomplished using 50,000 frames of data in this manner, 10 times the original objective, and over 32 hours of additional video data with the system implemented in real-time and connected to live camera sources. Two all-day evaluations also have been conducted, where system performance was evaluated from dusk to dawn, once in summer and once in winter. In addition, comparisons of passage and presence detection capability have been made directly with loops in the field, and speed detection has been verified by comparison to speeds measured by radar.

Details of these evaluations are included in the body of the report, but to summarize, these WADS algorithms have demonstrated detection capability comparable to loops under a wide range of previously difficult conditions: night and day, dawn and dusk, snow and rain, shadows and headlight reflections. Further evaluation must be conducted to completely characterize performance under each particular condition.

The original objective of Task F (WADS Real-Time Hardware/Software Specifications and Development Plan) was to generate a specification for a real-time implementation of WADS and a plan to develop it. However, since this has already been accomplished under a different contract, this effort was retargetted toward the necessary specifications and plans for a real-time implementation of specific **applications** of the WADS technology, i.e. freeway incident detection or critical intersection control.

3 BACKGROUND

The objective of this section is twofold: first, to provide a brief critical review of the existing literature and development on video based vehicle detection, and second, to familiarize the reader with earlier and other ongoing research related to vehicle detection through video image processing performed by the research team. The synergy between research efforts conducted by the contractor resulted in rapid progress toward the common objective of producing a viable new technology for vehicle detection and automatic surveillance.

History of Video-Based Vehicle Detection

Research on image processing for vehicle detection began during the 1970's in the U.S., Europe, Japan and Australia. A recent survey of the technology is presented in reference 3. In the U.S., research on this topic was initiated by the FHWA. (See references 4,5,6.) Although the major objective of this project was individual vehicle tracking, algorithms for vehicle detection and speed measurement were also developed. The original imaging system, also called Wide Area Detection System (WADS), was evaluated and recommendations were made for improving the hardware and software design of the WADS system.[7] The technical problems and issues associated with that WADS system are discussed in detail by the authors.[8] Briefly, although the work performed in the FHWA study was pioneering, the WADS system developed was too primitive for practical application, something that might be expected at the initial stages of new technological developments.

In Europe, several countries are currently funding research and development on this subject. Examples include: (1) the work in England on image processing applied to traffic begun at the University of Manchester Institute of Science and Technology

(UMIST) and continuing at Napier Polytechnic, the University of Sheffield, the University College, London, and the University of Leeds, (2) a vehicle tracking system being developed in France by the National Research Institute for Transportation and Security (INRETS), and (3) a real-time multispot detection system being developed in Belgium by Devlonics, Ltd. (See references 9, 10, 11, 12, 13, 14, 16, 17, 18, and 19.) Each of these efforts is briefly discussed below.

The UMIST project utilized a solid state camera generating a 100x100 pixel per frame image at 8 frames per second.[9] The camera was mounted at a height of 73.8 ft (22.5 m) above a two-way highway and data was collected during a period in which illumination varied by a factor of four. The camera output was digitized and averaged. An image corresponding to road background in the absence of any vehicle was stored in the memory of the digital processor. During operation, the digitized image is subtracted from the reference image to generate the road background. In the absence of vehicles the two images should be similar and therefore their difference is due to noise and changes in illumination. A threshold then is used to compare it with the difference of the two images. The resulting binary image is compressed and stored on videocassette and processed in the laboratory. This system was not implemented in real-time and would only work in ideal conditions where the background did not change significantly and where there were no common artifacts such as shadows and reflections to cause false detections. Current work is focused on the combination of microcomputer based imaging processing hardware and neural-network pattern recognition techniques.[10] No details were available on performance in the presence of artifacts.

Currently the system being developed at the University of Sheffield operates under the assumption that the roadway background does not change significantly over a period of 1 minute, which is considered to represent ideal conditions.[11] This approach is highly prone to errors due to illumination changes, shadows and reflections. More recently researchers at the University have concentrated on vehicle recognition based on vehicle outline template matching.[12]

At the University College, London, the focus is on implementing vehicle tracking on real-time parallel image processing computer architectures.[13] This vehicle detection approach requires a background to be manually sampled, which is impractical in field situations. Work is underway to automate this background estimation. Once objects are separated from the background, features needed for vehicle tracking are extracted. The features being extracted would result in tracking not only vehicles but also common artifacts, such as shadows and reflections, which would generate a substantial number of detection false alarms. A more recent development is a departure from this previous work.[14] The thrust is to extract qualitative information from the traffic flow rather than quantitative. The system detects the formation of queues on the motorway. This system cannot count vehicles, it only gives queuing information. In addition, the system is yet very preliminary.

The University of Leeds has developed a system known as TULIP (Traffic Analysis Using Low-cost Image-Processing) based on off-shelf technology. The system can currently only process information from one lane of traffic with two detection spots placed by the operator. The operator must then select a method to detect the vehicles (determine the vehicles from the background) probably depending on the illumination available. The system does not appear to be working during congested flow conditions. This system has been combined with Wootton Jefferies Consultants's VISTA system to provide information in simple traffic situations (straight level roadways as contrasted to tracking vehicles at roundabouts). No information was available on performance in other types of artifact situation such as shadows, weather (rain, snow, fog, wind, or dawn/dusk transitions).[15]

In France, INRETS is also developing a real-time vehicle tracking system.[16] The system first automatically determines the roadway lane positions and then tracks vehicles down each lane through the camera's entire field-of-view. The major problems with this system are that it can lock onto common artifacts such as vehicle shadows and reflections, and has problems tracking vehicles through various background changes (e.g. asphalt/cement boundaries, building shadows) and in congested situations where the tracking mechanism breaks down. Some observed test sequences indicated that dark shadow areas under vehicles were the primary objects being tracked and not the vehicle itself. Moreover, according to a recent paper, the geometrical shape of the shadow was relied upon for the detection process.[17] This would present difficulty in adapting the system for different times of day and different types of cloud cover. In addition, completely separate approaches have been devised for detection during congestion and detection at night, which leaves open the question of the approach during congested transitional periods, i.e. wintertime rush-hours. INRETS is currently developing a dedicated processor with capability of handling one frame of video data every quarter of a second, which implies throughput of their system will be limited to 4/30ths of real-time speed.

Recently, Devlonics, Ltd. of Belgium has advertised a real-time system which appears to accommodate up to four detection spots, each covering a 32.8-ft (10-m) lane area.[19] The approach taken, which originated in cooperation with the Catholic University Leuven, is to detect vehicles relative to an automatically determined reference background and track their movement through the 32.8-ft (10-m) area so as to also determine vehicle speed.[18] Little detailed information about the approach taken is available; however it was learned that vehicles must move through the 32.8-ft (10-m) area in less than 2.5 seconds or they become part of the background signal. Furthermore, a microcomputer is needed to implement the detection for each spot, so the full four detection spot system requires four microcomputers. The system does not seem to operate in real-time but with a 5-second constant decision delay which is too long for critical intersection control applications. Once again, no detailed information is available about system performance in the presence of artifacts.

The Japanese government sponsored Institute of Industrial Science, University of Tokyo, research on measuring traffic flow using real-time video processing. (See references 20,21,22, and 23.) Of interest is the nonimaging sensor designed by Shigeta and Ooyama.[24],[25] The sensor is an array of photoelectric elements with geometry designed to match the perspective distortion produced by the camera installed at a specific height and angle of view. The photoelectric elements have a spectral response with a maximum of 930 nm. This response is thought to be optimum during the complete 24-hour day/night cycle. Detection is achieved by difference of illumination received by pairs of sensors. The distance between sensors in a pair is known. By measuring the time difference between detection by the first and the second element in a pair, the speed of the vehicle can be estimated. This system was tested in Tokyo for 2 years. The system, which is the most cost-effective, is not truly an imaging system and cannot be extended beyond simple detection as it requires fixed roadway placement geometries and has only fixed and discrete detection points in the field of view. Investigation is now underway in Japan to look at the application of image processing equipment to the vehicle detection problem.[26]

The Australian Research Board has developed a real-time vehicle presence system.[27] The system allows placement of up to 16 detection spots at any position in the camera's field-of-view via front panel thumbwheel switches. To determine the background level, an additional reference detector is required which must be placed in an area free of vehicles. This reference is compared with the outputs of each of the detection spots and when fixed thresholds are exceeded, a vehicle is detected. Each detection spot has a manual offset adjustment to compensate for the difference in road surfaces between the reference and detector areas. The approach works adequately for ideal situations but the system cannot distinguish the difference between vehicles and major artifacts such as vehicle shadows, reflections and building shadows. Also, since the detection algorithms are hard-wired, there is no flexibility to reprogram and improve the system. This system has been used to monitor the flow of vehicles at a single location on a "carriage-way", and as a tool for monitoring movement into and out of a parking lot.[28]

Experience with machine vision over the past 5 years suggests that despite the impressions generated throughout the literature, a reliable, fieldable, cost-effective, real-time multispot vehicle detection system operating under all weather and artifact conditions is still lacking. The major problems with the aforementioned research systems and products, that have been addressed and resolved by the WADS system presented in this report are as follows:

1. Automatic adaptation to a wide variety of roadway backgrounds without reference marks.

   The inability of existing systems to automatically adapt to a wide variety of backgrounds prevents them from running reliably or autonomously. A unique approach to estimating the background at the detection spot was therefore developed; this allows automatic adjustment to any uniform or nonuniform road surface.

2. Operation in the presence of common artifacts such as shadows, illumination changes and reflections.

   Prior approaches have not really addressed common artifacts such as shadows, illumination changes and reflections. This has resulted in these systems having high false alarm rates under these conditions. In the WADS system, these problems were resolved using a vehicle signature based detection approach that can differentiate vehicles from these artifacts.

3. Operation in congested or stopped vehicle conditions.

   Congested traffic conditions and stopped vehicles have caused the loss of the vehicle and erroneous background estimation in prior approaches. The WADS system allows vehicles to stop for much longer periods of time without "blending" into the background.

4. Arbitrary placement of any type of detector in any configuration anywhere within the camera's field-of-view.

   Most existing systems only support a small number of fixed position detectors. In contrast, using the WADS system one is able to place any number, size and shape detection spots anywhere in the camera's field-of-view and can reposition these spots dynamically under software control. This is accomplished without requiring the camera to be placed at a fixed height or angle.

5. Cost effectiveness, real-time operation and programmability.

   Existing approaches to cost-effective, real-time implementations have resulted in oversimplification of the sensor, hard-wiring the detection processing or using cost-prohibitive processors. Cost effectiveness was a major consideration in the development of the WADS detection system. The system can operate with standard video cameras; no specialized sensors are needed. The approach taken in developing the WADS system allows operation in real-time with full programmability. By using an IBM AT compatible personal computer for WADS rather than an expensive image processing platform, the final system implementation is cost effective.

Related Funding for Developing the Minnesota WADS System

The breadboard system developed detects vehicle presence, passage, and speed in real-time with performance comparable to magnetic loop detectors. Advantages of this system over loops include the ability of a single system to simultaneously monitor multiple locations over a wide area of road, and the unique ability to reposition detection locations without disruption of traffic or cutting of pavement.

One application of this system will be preprocessing of video from traffic surveillance cameras in order to automatically alert surveillance operators of abnormal traffic conditions (incident detection). In addition, the system could be an important tool for transportation planners, allowing for the flexible collection of traffic data, i.e., vehicle counting and classification, derived from either live cameras in the field or videotape in the office.

In 1984, an initial study was funded by Mn/DOT to determine the feasibility of detecting vehicles using video.[1] During this phase, schemes for video-based detection of vehicles were surveyed to appraise interest of the traffic control community as well as to evaluate previous development attempts. Functional requirements of a video-based detection were then defined including derivable traffic data, accuracy of measurements, the environmental conditions under which detection must occur, expected reliability, compatibility with existing equipment, and range of operation. A database of colocated visible and infrared video data was collected from nine different locations in the Minneapolis-St. Paul area, with day, night, and varied weather conditions represented. Preliminary algorithms for presence, passage, and speed estimation were then developed and evaluated on collected data. The result was an algorithm for detecting presence and passage based on a combination of temporal and spatial features. Performance limitations due to visibility, occlusion, and artifacts were studied. Finally, in Mn/DOT Phase I, different potential sensor configurations were studied, and environmental constraints relative to the camera and processing electronics were estimated.

The findings of the Phase I study were very promising. Passage detection during daytime was 98 percent accurate with 1 percent false alarm rate, and 94 percent during nighttime with 6 percent false alarms. Speed was determined to be accurate within 15 percent at 60 mi/h (96 km/h) and 7 percent at 30 mi/h (48 km/h). It was determined that a real-time video detection system could be built largely with existing technology, using off-the-shelf components. A visible-light video camera was chosen as preferable to an infrared video camera, based on both performance and cost (results with the infrared camera were 70 percent daytime detection, 3 percent daytime false alarms, 92 percent nighttime detection, 1 percent nighttime false alarms).

It was concluded that night, rain, and snow did not present insurmountable difficulties for vehicle detection. Fog, however, could always be a problem, depending on the severity. However, in conditions where fog is severe enough to create a problem for video-based vehicle detection, drivers of vehicles would have such limited visibility of traffic lights and taillights of other vehicles that they would be best advised to pull off the road, wait it out, and not attempt to drive under such dangerous conditions. Traffic lights would operate in a pretimed mode in such a case.

The average installation cost per intersection was estimated to be 30 percent lower than loop detectors and maintenance cost was estimated to be 35 percent lower.

Following the successful completion of the feasibility study, a phase II contract, entitled "Breadboard Fabrication and Testing", was then awarded. Work on this contract began in 1985, and was recently concluded in December 1988. The overall objective of this project was the design and implementation of a system capable of doing robust video-based vehicle detection in real-time, under fair weather conditions, i.e. without the presence of serious artifacts such as snow, headlight reflections, occlusion, camera motion, etc.

For the Mn/DOT Phase II contract the necessary set of software and hardware modules were developed to implement a real-time vehicle detection system, some of which were then reused to construct the necessary algorithm development facility for the FHWA project. Several ancillary tools were constructed for various support functions: a video disc interface for seeking and playing of sequences of frames on video disc under program control; a detector placement editor for set up and editing of arbitrary detector configurations; and a ground truth editor to facilitate entry of the manually-derived traffic parameters used to evaluate system performance.

A software module was devised to extract average image intensities under each element in a detector. This module, termed the software formatter, was not capable of operating in real-time (i.e. 30 frames per second) and instead single-stepped the video disc when ready for a new image. Subsequently, a hardware implementation of the software formatter was created, the hardware formatter, which allowed for the real-time extraction of detector intensity values. The real-time hardware formatter, developed along with its necessary attendant test and set up software, was integrated into a real-time control system that repeatedly applied the detection algorithms to frame after frame of video data.

In addition a result recorder was developed, which can be described as another real-time system, hosted on another PC separate from detection system, which monitors system performance and displays traffic measurements on a time-averaged basis, emulating the capability of a loop controller.

Funding from various sources other than FHWA for the development of a video-based vehicle detection system has been made available to the research team. Improvements to the WADS system for generatation of various indicators of energy efficiency with respect to traffic flow are in progress. To this end, additional detection algorithm development, especially with respect to congestion, improvements to the design of the hardware formatter, and to address problems encountered with adapting the system to work around the clock on existing surveillance facilities are being performed. Other efforts warranted in the attempt to improve the WADS technology have been initiated to aid in the necessary transition of this technology from research lab to the field.

4 WADS HARDWARE DESIGN/PROCUREMENT

The objective of this task was to assemble a facility to collect WADS video data as well as to support continued development of WADS algorithms and software. The following sections give an overview of the data collection equipment that was utilized, and then describe the WADS algorithm development facility integrated on the COMPAQ 386 from existing software components.

Camera sensor types were reviewed in Phases I and II [(1)], along with the WADS efforts that were applicable for video traffic data collection: solid state (CID,CCD), Near-IR sensors, far-IR, Vidicon and specialized sensors. (See references 4,5,6, and 7.) It was determined that all normal video cameras can provide satisfactory performance.

The cameras were mounted in environmentally controlled enclosures with remote controlled pan/tilt mechanisms to allow the camera to view an entire area surrounding the mounting position. The cameras were equipped with a remotely controlled power zoom lens to vary the field-of-view magnification from 10 to 70 degrees (a Canon 6-75 mm lens meets this).

In the Mn/DOT Phase II effort, hardware and software components necessary to demonstrate video-based vehicle detection in real-time were developed. For this project, these components were configured into an algorithm development facility that was subsequently used to improve the baseline algorithms in order to deal with artifacts such as shadows and nighttime.

This WADS algorithm development facility is based on a COMPAQ Deskpro 386 microcomputer (fully IBM AT compatible, except faster). A digitizer/display card, video monitor, graphics monitor, optical video disc player, and mouse are configured with

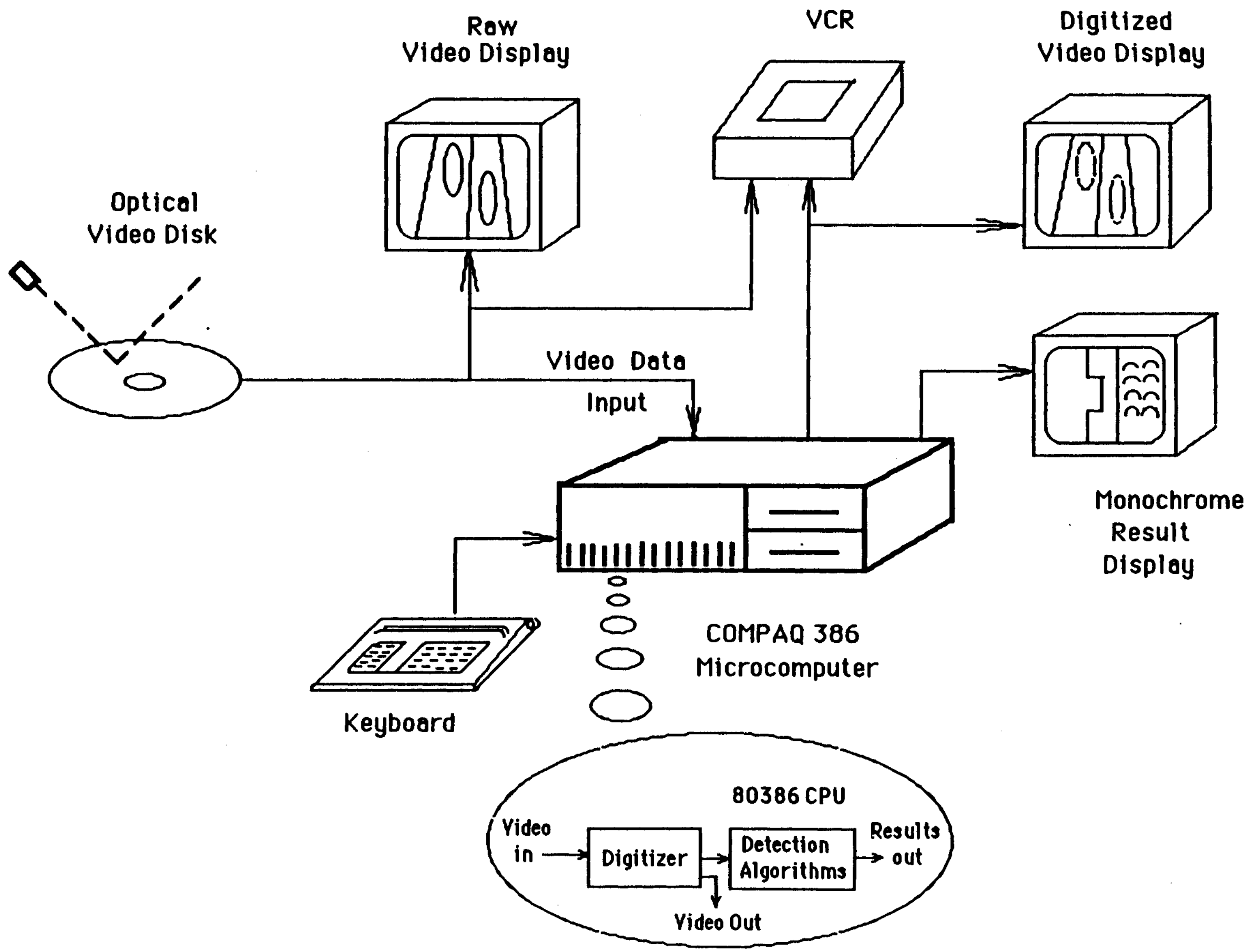


Figure 2. WADS algorithm development facility.

the COMPAQ (see figure 2). The facility "hardware" is rounded out with the software formatter (a software emulation of the real-time image preprocessor developed under a different contract).

All software development was done in the C programming language, which gives the maximum flexibility in integrating future hardware and software capabilities. Algorithm and software development on the AT were further supported by the Foresight Software package. Foresight Software consists of a command processor useful for interactive algorithm development, and an underlying collection of C callable functions that supports signal/image processing and signal/image file handling.

Foresight is built around one file system that manages access to image files and a second file system that manages access to feature vector files. Device independent image files can reside on disc as well as specialized digitizer and display devices. Feature vector files contain collections of linear signals that represent features (i.e., measurements or statistics) over time or other possible dimensions.

The Foresight command processor, called V3COM, allowed for the interactive manipulation and processing of these files, usable without dealing with a programming language like C. Various algorithmic approaches were prototyped with V3COM command files, which were simpler to write than the corresponding C code. Command files process data, with input, output, and intermediate results stored in image files and feature vector files. The results of processing were interactively analyzed by displaying image files to the image display card, and plotting the contents of feature vector files on the IBM graphics card. When algorithms attained a certain maturity they were reimplemented in C.

In addition to supporting algorithm development, the image and feature vector file systems were used as a basis for integrating existing software components into the WADS algorithm development facility. They provided a common data format for the storage and access of intermediate and final results, and allowed for the interactive inspection (via V3COM) of these results as warranted.

Certain modifications to existing software components were undertaken on this project to allow them to be integrated into the WADS algorithm development facility. In addition the detector placement editor was modified to support a) mouse and menu driven detector layout, b) increased number of detector configurations, and c) calibration of image based on input of real-world landmarks.

The software structure of the WADS algorithm development facility is depicted in figure 3. Each box represents a stand-alone program that can be executed with a DOS command line. Data is transmitted between the boxes via feature vector files, image files, and one specialized file that contains detailed information on the detector layout and other configuration parameters. A typical scenario of use is as follows:

1. Data on the video disc is reviewed and a sequence of frames selected via the sequence selector (SEQ). A sequence of frames is indicated by a start frame and number of frames or, alternately, a start and stop frame. This creates the sequence configuration file.

2. The detector configuration (or detector placement) editor (PSAS) is invoked, which positions the video disc at the first frame of the sequence. Detectors are laid out, either cross-lane or down-lane, via the interactive mouse-driven interface. The user positions each detector and selects the

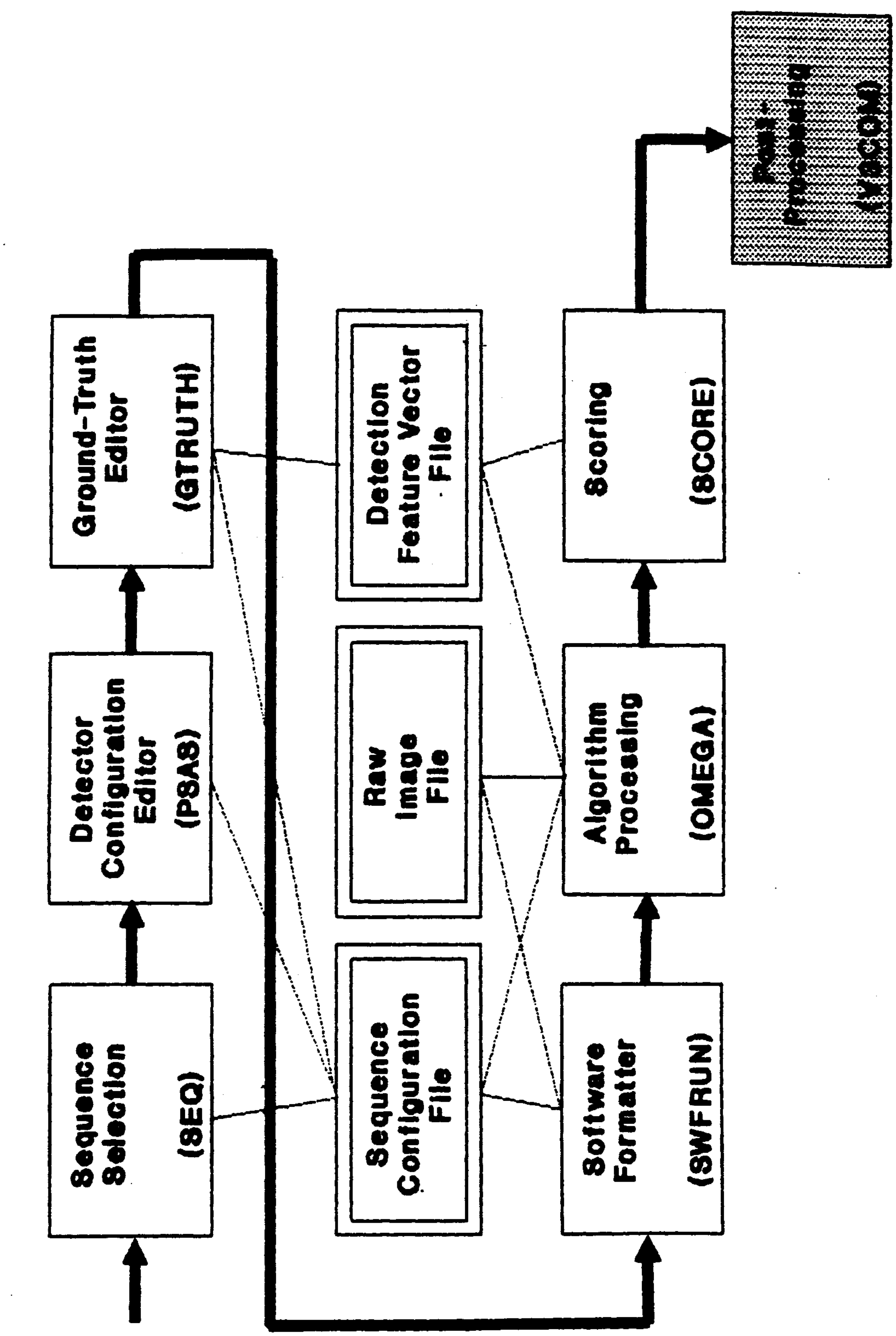


Figure 3. Software modules of WADS algorithm development facility.

number of vertical and horizontal elements. Optional detector pairs can be set as speed traps. This information is output to the sequence configuration file. Calibration is optionally performed by locating two objects within the field of view of identical size and entering the known real-world measurement of the distance between them. On the freeway this can be accomplished with lane-markers that divide lanes, spaced at a known distance. Finally, speed traps are indicated to pair detectors for use in estimating vehicle speed.

3. The a priori presence and passage information for this sequence is manually entered using the ground truth editor (GTRUTH), and stored in the detection feature vector file. This is done by overlaying each frame of the sequence with a graphical representation of the detector layout, and entering presence/passage information by pressing mouse buttons.

4. The average intensity values for each detector are extracted for every frame in the sequence and stored to the raw image file. The software formatter (SWFRUN) accomplishes this by single-stepping the video disc to each frame in the sequence, digitizing each frame, and then using the CPU to generate average intensities for each detector. Each row in the raw image file corresponds to a specific frame on the video disc.

5. The WADS algorithms, embodied in OMEGA, are applied to the output of the software formatter (an image file) to derive presence and passage information. Speed is derived if speed traps have been set up and calibration has been performed. The results are inserted in the detection feature vector file created by ground-truthing.

6. The SCORE processor compares the presence, passage, and speed output by OMEGA with the ground-truth data entered via GTRUTH. All of this data is contained in the detection feature vector file. Output is to the screen or a disc file.

7. V3COM is used for further post-processing of the presence, passage, and speed measurements stored in feature vector files, as well as the raw image file generated by the software formatter.

5 WADS DATA COLLECTION

The objective of this task was the selection of field sites for collection of WADS video data, installation of necessary instrumentation, and recording of WADS video data under typical conditions for which the WADS image recognition algorithms are expected to operate.

Data was collected from both existing freeway surveillance locations (primarily in Minnesota as well as in Florida, Maryland, Michigan, and California) and the dedicated freeway/intersection site (in Minneapolis, Minnesota). Data had already been collected this way in the Phase I and II contracts. In Phase I, mobile data collection equipment was used but it was difficult to get desired conditions and to collect data from realistic camera positions (i.e. as they would be in a final system). In Phase II cameras were used in the Mn/DOT freeway surveillance system and it was found to be advantageous to collect diverse video data from more than one location.

Data also was collected using the freeway surveillance system cameras of the Florida DOT (in St. Petersburg), Michigan DOT (in Detroit) and the Maryland DOT (in Baltimore). In addition, some data was collected from an intersection surveillance system installed in Los Angeles, California.

A camera mount was installed at an intersection in the Mn/DOT Phase II project which was used in the WADS data collection effort. This location was unique since the camera could be moved by remote control to capture incoming or outgoing traffic on both the street (Lyndale avenue north and 42 street) or the freeway (I-94).

Data was collected under a variety of traffic, time-of-day, weather and artifact conditions (see table 1).

Previously data was collected for most of these conditions in the Mn/DOT Phase I and Phase II efforts and this was ongoing in Phase II. The data collected in these two efforts was summarized in the interim report. This database was augmented with more of the artifact and traffic conditions necessary for the WADS algorithm development effort; this entire database is summarized in table 2. The video database was increased by eight times its original size at the start of the contract.

Table 1. Data collection conditions.

Times-of-day	daylight, dawn, dusk and night times of the day.
Vehicles	passenger cars, trucks and commercial semi-trucks, buses as well as other vehicles such as ambulances, motorcycles and road equipment.
Traffic patterns	multiple lanes (including turn lanes), normal traffic, turning vehicles, congestion, long queues and stopped vehicles.
Weather cond.	clear, overcast, fog, abrupt lighting changes (e.g. lightning at night, camera AGC shifts), very cold and hot temperatures, heavy snow and rain and haze.
Artifacts	glare (due to sun or lights), shadows (from other vehicles, moving clouds and slowly moving shadows such as from signs, buildings and poles), objects blowing on the roadway (paper, snow), people walking on the road, camera motion due to wind or road vibrations, reflections (off wet roads, headlights), occlusion (vehicles blocking the view of other vehicles) and spots on the camera housing windshield.

Table 2. WADS video data collected.

Condition	Total
Total minutes	6123
Times of Day:	
day	3905
dusk	1364
night	2286
dawn	590
Vehicles:	
emergency veh.	28
road equipment	133
Traffic:	
intersection	1355
freeway	4768
on coming	2546
going away	3622
Heavy traffic	1288
Medium traffic	1503
Light traffic	2912
congested	708
stopping	1672
incident	288
lane drop	70

Table 2. WADS video data collected (cont'd).

Condition	Total
<u>Weather:</u>	
Heavy rain	170
Light rain	278
Heavy fog	5
Light fog	25
lightning	58
Medium sleet	0
Light sleet	724
Heavy snow	0
Medium snow	190
Light snow	287
haze	0
accum. snow	1719
blowing snow	682
clear	2595
part cloudy	48
overcast	2555
<u>Artifacts:</u>	
car shadows	979
cloud shadows	364
Other shadows	436
road glare	173
sun glint	421
object on road	0
wind motion	4
vibrations	0
spots on lens	237
glare on lens	260
wet roads	2188
water plumes	204
color video	230
agc flux	157
blooming	929
streaking	71

6 WADS DATA ANALYSIS

The objective of this task was to analyze the WADS field video data, transfer selected data to a video disc, and augment this database with manually entered traffic measurements in order to automate evaluation of the algorithmic performance.

The plan at the start of the project was to create two video discs, each 15 minutes long, one video disc for algorithm development, the other for algorithm evaluation. This would allow for an unbiased evaluation by testing the algorithms on data that had not been analyzed during development. The same basic approach was followed, except a video disc created earlier under the Mn/DOT Phase II contract was used for algorithm development and a new single 30-minute video disc created in this project remained largely unused prior to algorithm evaluation in task E.

The collected videotapes were manually screened for the weather, traffic, and other conditions shown earlier in table 1 and transferred to a 30-minute optical video disc containing over 54,000 image frames. The data from this disc is summarized in table 3. The data comprises shadows, snow, rain, and congested traffic. Also included in table 4 is a summary of the sequences available on the Mn/DOT optical video disc.

A video disc is an extremely convenient medium for storage of sizable numbers of image frames (54,000 frames or 30 minutes of video). The extraction of detector data by the software formatter takes longer than one thirtieth of a second, making the video disc necessary to hold each video frame constant for this extended time. In addition, the video disc made for almost perfect reproducibility of video sequences, with greater than 7 out of 8 bits accuracy when digitized, and absolute frame positioning accuracy.

The appropriate traffic parameters (presence, passage, speed) for each sequence on both video discs were manually extracted and recorded to the COMPAQ Deskpro 386 hard disk. This information is referred to as "ground truth" data and is used to compare against the algorithm results for "scoring" purposes. This approach was used to track the changes in performance as algorithms were modified and reapplied to the Mn/DOT Phase II video disc. It will also be the basis of the final evaluation of the algorithms across the 30-minute video disc, resulting in an automatically repeatable verification of system performance.

Table 3. WADS 30-minute optical video disc sequences.

Location	Duration (Seconds)	Conditions
Maryland, I-695	300	Vehicle/Cloud Shadows, Normal Traffic.
Mn/DOT, I-94	60	Dusk, Heavy Rain, Lightning, Spots on Housing.
Mn/DOT, I-94	90	Night, Heavy Rain, Lightning, Spots on Housing.
Mn/DOT, I-35W	60	Dusk, Wet Road, Light Rain.
Mn/DOT, I-35W	60	Night, Wet Road, Light Rain.
Tampa Bridge	60	Heavy Traffic, Occlusion.
Mn/DOT, I-94	60	Heavy Snow, Headlight Reflections, Snow on road.
Mn/DOT, I-35W	60	Heavy Snow, Clear Road, Large Snow Flakes.
Mn/DOT, I-94	60	Rain, Spots on Housing.
Tampa Bridge	180	Hazy, Heavy Traffic.
Mn/DOT, I-35W	90	Asphalt/Cement Transition.
Tampa Bridge	144	Stop & Go Traffic.
Mn/DOT,Intersection	96	AGC Fluxes, Wind, Glint.
Mn/DOT,Intersection	180	Intersection Stop Line.
Mn/DOT,Intersection	270	Day, Wind, Near-IR Camera.
Mn/DOT,Intersection	60	Day, Wet Pavement.

Table 4. Mn/DOT 14-minute optical video disc sequences.

Location	Duration (Seconds)	Conditions
Mn/DOT,I-694	34.9	day, trucks, vehicle shadows, normal traffic.
Mn/DOT,Intersection	44.9	night, headlight reflections
Mn/DOT,Intersection	30.0	night, headlight reflections
Mn/DOT,Intersection	62.0	day, bicycle, AGC fluctuation
Mn/DOT,Intersection	19.0	night, headlight reflections
Mn/DOT,I-694	28.1	day, shadows, overhead sign shadow
Mn/DOT,Street	16.9	day, shadows, AGC fluctuations, glint
Mn/DOT,I-35W	10.0	day, car/overpass shadows
Mn/DOT,Intersection	28.0	dawn, heavy fog
Mn/DOT,I-694	21.0	dawn, light fog, damp road, trucks
Mn/DOT,I-694	14.6	day, overcast, trucks
Mn/DOT,I-694	22.1	day, overcast, motorcycle
Mn/DOT,I-694	28.9	day, overcast
Mn/DOT,Intersection	23.0	day, motorcycle
Mn/DOT,Intersection	34.1	dusk, pavement reflections
Mn/DOT,I-694	55.0	dusk, pavement reflections, exhaust plumes
Mn/DOT,I-35W	36.0	dusk, pavement reflections, AGC fluctuations
Mn/DOT,I-694	31.2	night, pavement reflections
Mn/DOT,I-35W	27.8	day, car shadows
Mn/DOT,I-694	31.1	day, on-ramp, car shadows, near-IR camera
Mn/DOT,I-35W	18.0	day, car shadows, pavement reflection
Mn/DOT,Intersection	19.2	day, car/pole shadows
Mn/DOT,I-694	19.9	day, car shadows
Mn/DOT,Intersection	83.0	dusk, pavement reflections, noisy image, motorcycle
Mn/DOT,Intersection	14.9	night, pavement reflections
Mn/DOT,I-35W	14.9	day, CCD camera
Mn/DOT,I-35W	15.1	night, CCD camera
Maryland,I-695	15.2	day, car/tree shadows, stopping traffic
Mn/DOT,I-35W	22.2	night, wet road, headlight reflections, water plumes

7 WADS ALGORITHM DEVELOPMENT

Prior to the commencement of this project, the research team had developed vehicle detection algorithms that performed well under fair-weather conditions. However, these algorithms did not adequately handle several less favorable operating conditions, or artifacts, that would commonly present themselves in eventual applications. The objective of this task was to devise solutions for dealing with shadows originating from moving and stationary objects; headlight reflections at night; glare from reflected sun during the day; changing illumination such as at dawn or dusk, during partial cloud cover, or stemming from fluctuations in a camera's automatic gain control circuitry (AGC); and finally the reduction in image quality during snow and/or rain. During development and testing of the algorithms it became apparent that congested heavy flow traffic conditions posed some special problems that also had to be resolved.

This section describes how the handling of the artifacts was addressed. As an introduction to this discussion, an overview of image processing is first presented, with regard to how it can be applied to the problem of video detection. This is followed by a discussion of specifics regarding the construction of approaches to dealing with artifacts.

Image Processing Applied to Vehicle Detection

Research on image processing for traffic control applications began to evolve during the mid-1970's because of the potential improvement to vehicle detection technology that it offered, and the increasing cost effectiveness of the component technologies. One image-processing system could replace any number of loop detectors within a single camera's field-of-view. Most dramatically, an image-processing system would allow for the dynamic placement of detectors, under the direction of a real-time traffic control system. The analogy in conventional detection technology would be loops that crawl by themselves along the road surface. Finally, the availability of microprocessors and their associated standard platforms, with large markets of third-party supplied hardware devices, makes the implementation of imaging detectors feasible and cost effective.

Figure 4 shows the architecture of a typical imaging detection system. A video camera generates an image once every 30th of a second. Each frame is composed of two interlaced fields, where each field is scanned in a 60th of a second. Typical dimensions of a digitized image (converted from analog by an image digitizer) are 512 lines per frame, with 512 pixels (picture elements) per line. An individual field is 256 lines per frame, with 512 pixels per line.

Typically, each pixel will contain an 8-bit grey-level intensity value, ranging from 0 to 255. Storage of a single frame requires 256 KBytes of RAM memory. If it were necessary to process every pixel in the image every frame time, it would require 8 MIPS (million instructions per second) of throughput per necessary instruction. For this reason the image is typically segmented into regions of interest as soon as possible after digitization. Fortunately, for vehicle detection, the regions of interest where vehicle detection is to occur can be preselected, making the segmentation phase deterministic and efficient. Subsequent processing of the image data is restricted to these regions, thereby significantly decreasing the computational and storage requirements. As a result, real-time implementations of the video-based vehicle detection enter the realm of feasible.

The intensity values collected from the preselected regions of interest are further processed to extract descriptive measures, or features, of the region. Features are typically

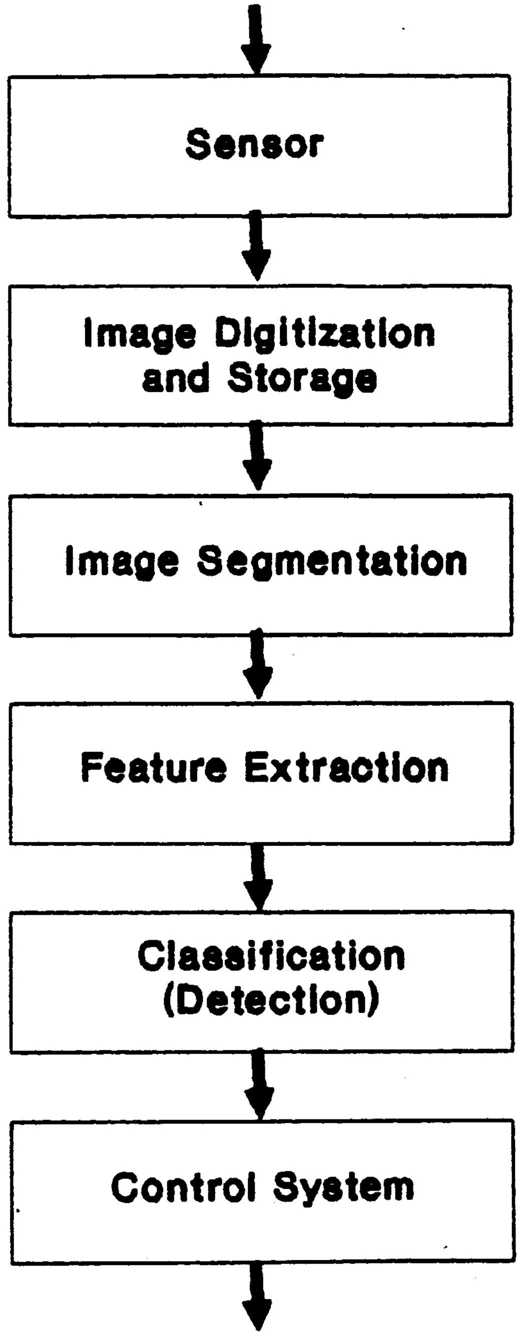


Figure 4. Typical image detection system.

based on various statistics or estimates of the data, but can also be derived from state machines that combine information (features, state information, etc.) in some a priori determined fashion. The work in designing the feature extraction section of an imaging detection system is usually in discovering the set of features that embodies the necessary information in order to make a robust detection decision.

Once features are extracted, a classifier processes them to arrive at a detection decision. The major issues in classifier design are those of sufficient detection capability, avoidance of erroneous detections (or false alarms), and the robustness of the detection decisions under varying conditions. Varying conditions are handled by values or thresholds within the classifier that are continually updated to reflect current conditions. This update can be driven by a recent history of feature values, or itself be the result of another classification process on ancillary data. For example, for video-based vehicle detection, it may be desirable to have a clock/calendar module which constantly updates an estimate of expected luminance of the sun (or moon), in order to set intensity thresholds. Typically there is a tradeoff to be made between the complexity of the mechanism that makes the detection decision, and the complexity of the mechanism that is continually adapting detection thresholds. For instance, neural-network technology has been proposed in the past for feature selection and classifier design. However, the author's do not view current neural-network technology as a panacea for coping with the inherent complexity of the feature selection and classifier design task. In some applications, neural-networks can be an effective tool to aid an algorithm designer in their search for a viable feature set, by automating the evaluation of a given feature set. However, the major drawback to neural-networks may be that they encourage a blind approach to feature selection and classifier design, in that the algorithm designer proceeds with no inherent understanding of how to map detection criteria back onto the real world. The algorithm designer would then find it difficult to formulate a model of why a detection approach fails under new conditions, and hence be hampered during the all-important phase of algorithm validation.

Often the intent of an adaptive mechanism such as the one mentioned above, is to characterize the expected signature when only background is present. Background is defined as the absence of that which is to be detected. In the case of vehicle detection, background is the road-surface with no vehicles present.

Finally, the detection decisions are transmitted to an external application or control system. For vehicle detection, this could be a controller that emulates the capability of a loop-controller, or some device of greater complexity, such as a freeway incident detection system or a traffic control system for an isolated intersection or network of arterial streets. In the next subsection the effort to design WADS algorithms is discussed, presented in the framework presented here.

Design of WADS Algorithms

It was initially determined that three detection decisions would be generated by the WADS algorithms: passage, presence, and speed. Passage and presence are closely related, in that for normal noncongested operation, the passage signal is the same as the rising edge of the presence signal. However in congested situations, where the presence signal is continuously high, it would be necessary to take an alternate approach to generating a passage signal. The output of the detection system was limited to these three basic measurements, because it was determined the balance of conventional traffic parameters can be derived from these. Traffic parameters taken into consideration include volume, occupancy, number of stops, percent delay, total travel, total travel time, space and time headways, and queue length.

Presence and passage detection signals are generated at each of the detection spots within the field of view. Detectors can be placed at any position in the camera's field-of-view and at any orientation, as illustrated in figure 5; these "pseudo-detectors" are interactively placed by the user, indicating where the image is to be "segmented" and average image intensity values extracted for further processing. Pairs of closely spaced detectors are used to estimate vehicle speeds. Detectors across lanes are used primarily for vehicle passage while downlane (or longitudinal) detectors sense vehicle presence. Multiple crosslane detectors can also be used for area presence.

The baseline detection approach relies on spatial and temporal features which are extracted for each detector. Spatial features provide information on vehicle signature regardless of its speed while temporal features respond to vehicle motion. Spatial features are relations between intensity values across a detector at any instant in time. Temporal features are taken for each detector over a number of time samples (i.e. over a number of image frame times). Temporal features respond to the motion of a vehicle.

The extracted spatial and temporal features are combined using sequential decision processing to generate both the background detection and vehicle presence and passage detection signals. Reliable background detection and its adaptation to a wide range of both uniform and nonuniform backgrounds is a key improvement over earlier approaches. Unlike other experimental units, in the WADS system presented here, the background is <u>automatically</u> determined by the system. No assumption is made about the road surface signature or its uniformity. Background

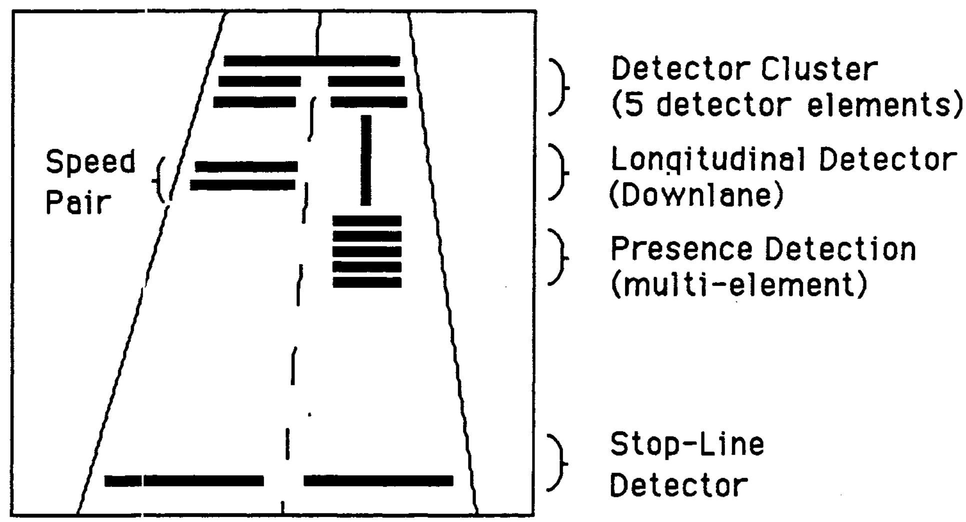


Figure 5. Example detector placements.

values are continuously updated and a special logic was developed for updating the background when a vehicle is not present. This logic prevents the background from being "lost" or falsely determined in congested or stopped vehicle traffic situations. Given reliable background estimation, vehicle detection is determined by differences relative to the background level.

The detection system described above performed adequately under ideal conditions, as documented in the next section of this report (Task E: Algorithm Validation). However, detection at night; and in the presence of rain, snow, shadows, and headlight reflections was problematic. This was to be expected, because algorithm design to date had not taken these artifacts into consideration.

Chief of all the artifacts to tackle was shadows, the largest population of artifacts in the database. The main shadows of interest were those created by moving vehicles, but shadows from stationary objects and clouds needed to be considered as well. Several artifacts had similar characteristic structure to shadows, allowing a single approach to fit them all. For instance, headlight reflections were viewed as "white shadows" in that normal shadows could be modeled as a negative gain applied to the normal signature of the pavement, and headlight reflections could be modeled as a positive gain applied to the signature of the pavement. Other gain and/or bias modifications of the background include camera AGC (automatic gain control) flux, dawn to day transitions, and day to dusk transitions.

Several approaches were considered in order to arrive at the final solution. A reasonable technique is based on median filtering of the detector signature, in order to remove the effects of shadows. This technique is described in appendix A, but it should be noted that it was not finally adopted.

It was also theorized that shadows could be separated from vehicles on the basis of low variability in spatial features (i.e. shadows are uniform and have low pixel intensity). This approach relied on the assumption that the negative gain effect of shadows would be fairly constant across the dimension of the shadow. In an ideal situation this would be the case, but, as it turned out, the amount and variability of the ambient illumination (reflections of direct sunlight from the atmosphere, vehicles, and surrounding structure) that impinged on the shadow made this a poor model. The reality was the shadow signatures evidenced as great a variability in image intensities as vehicles.

The eventual solution was to expand the baseline feature set to include edge-based features. They provide good separation between vehicle signatures and that of the unstructured (uniform intensity) artifacts such as shadows (vehicle, cloud, fixed objects), illumination changes (camera AGC, transition periods, lightning) and reflections (headlights, sun glint). This concept was tried on a shadow-rich subset of our video database. The result was the determination of a set of features which suppresses most of the false alarms associated with these common artifacts.

Vehicle speed was estimated by using pairs of closely spaced detectors and measuring the time it takes the vehicle to move between the detectors. This is shown conceptually in figure 6. By estimating the time t that it takes the vehicle to travel from the first detector **D1** to the second (**D2**) and knowing the distance between the detectors (**d**), the speed (**v**) can easily be estimated. For higher speeds, this time can be reliably measured using the difference in time between the passage signals generated by the vehicle detection algorithms (similar to a speed trap used with loops). In some situations (such as in congestion) the passage signal generation is not reliable enough to generate an accurate

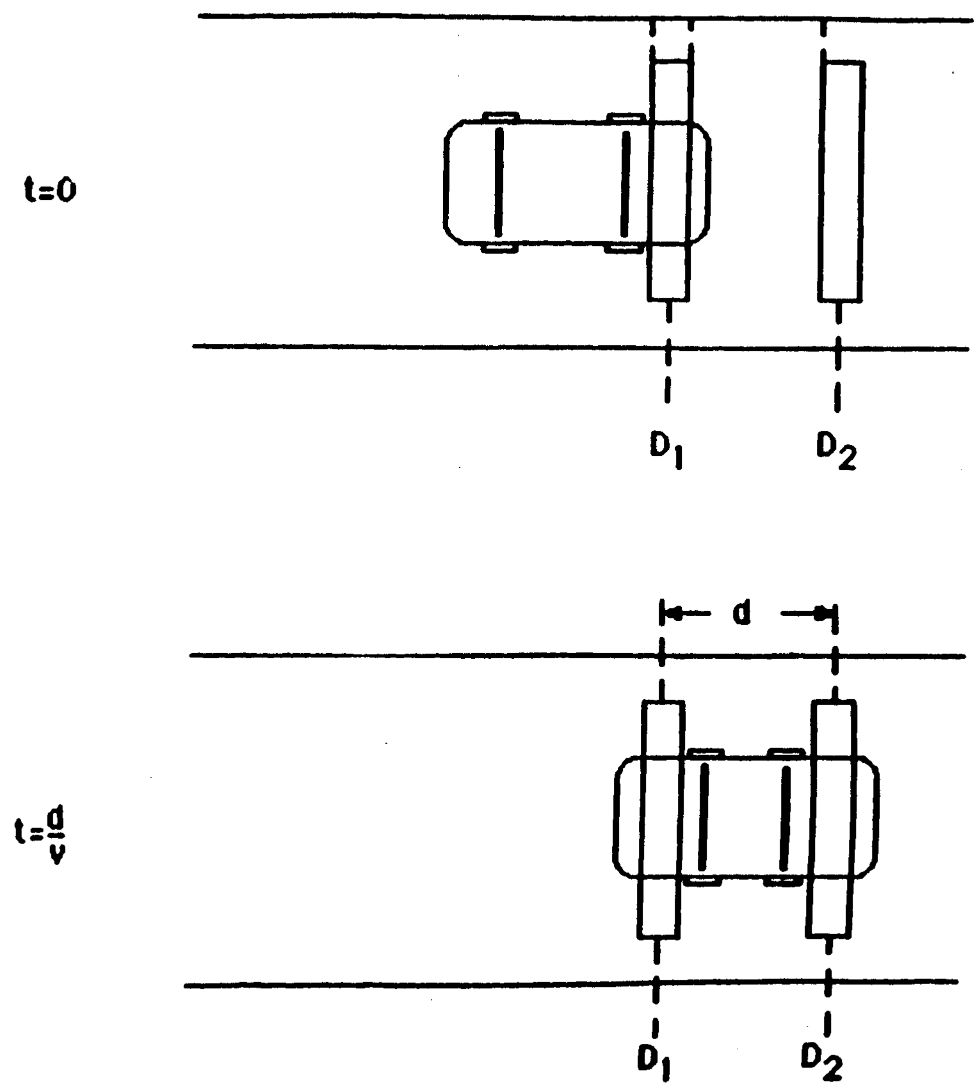


Figure 6. Speed detection.

speed measurement. As a result, a speed estimation technique that works independently of vehicle detection was developed.

The technique compares features generated by each detector and registers them in time using a signal correlation technique. This yields estimation of instantaneous speed as opposed to average speed so that the speed estimate can be used directly for improved control purposes. This technique does not have to rely on either the vehicle detection or background detection outputs.

In summary, the project team was able to devise an approach to passage, presence, and speed detection which effectively removes the impact of the aforementioned artifacts on detection performance. Snow and rain no longer have a corrupting effect. Shadows from vehicles in neighboring lanes are not erroneously counted. Headlight reflections are similarly ignored. Finally, system capability has been enhanced to the point where reasonable performance can be continuously observed around the clock, during night and day conditions, as well as dawn and dusk transitions.

8 WADS ALGORITHM VALIDATION

The objective of this task was to validate the algorithms developed in Task D by quantifying performance on at least 5,000 frames of diverse image data. In actuality, almost 36 hours of video data were processed. At 108,000 frames per hour, the original objective was exceeded nearly 800 times over. This was possible due to the timely availability of the real-time facility developed under the Mn/DOT Phase II contract.

Algorithms were evaluated continuously as development proceeded, in order to ascertain the level of improvement (or degradation) attributed to each new set of features or detection decision-making approach. This was done off-line, with video data from the optical video disc. In order to get a balanced overall measure of system performance a mix of artifacts was presented to the algorithms. Most likely this mix erred on the conservative side, presenting a concentration of artifacts whose occurrence exceeded the distribution to be expected in the real-world.

At the same time, an attempt was made to quantify how the algorithms worked on each individual artifact. However, more work remains to be done in this area. When coupled with tables of the expected distribution of each artifact in different localities at different times of year, the end result would be an ability to predict system performance in new situations (i.e. how well will the system work in Fairbanks, Alaska in January).

The system was connected on-line at Mn/DOT's Traffic Management Center, for two all-day evaluations, one in summer and the other in winter. System performance was ascertained in uncontrolled and unforeseen combinations of conditions that occurred over the course of these 2 days: sunrise, morning and evening shadows, congestion during rush hours, sunset, nighttime, as well as rain, snowy backgrounds, and wind.

Finally, in a related effort, overall system performance was evaluated in detail by reprocessing videotape data in the laboratory. For this study a direct comparison to actual loops in the field was made, by collecting video data from surveillance cameras that were colocated with Traffic Management Center loops.

The distinguishing factor between the off-line and on-line evaluation is the nature of the video data source. Off-line evaluation was performed using computer-controlled video sequences generated from a video disc. On-line evaluation was performed in real-time from video sources that were not under computer control: live data from traffic surveillance cameras at the Mn/DOT Traffic Management Center, as well as videotapes prerecorded from the same cameras.

The difference between the two data sources, and hence the approaches used to **score** the algorithms, is the repeatability. The video disc can endlessly regenerate the same sequence of video; it can start playing at exactly frame number 1000, and continue through to stop at exactly frame number 2000. A live camera cannot do this, of course, and with the available equipment, the videotape can only be repositioned within a second or two of the original position.

Because of the computer-controlled repeatability of the video disc, an approach for **automatic off-line scoring** of the algorithm performance was devised. This consisted of three steps: manual entry of **ground-truth** data, execution of the algorithms and storing of the results to disc, then automatic comparison of the ground-truth to the detection results. Separate techniques were devised for passage and speed scoring.

A technique for reliable automated scoring of presence detection remains to be developed.

For on-line evaluation a **manual on-line scoring** approach was devised that relies on a human observer counting the number of vehicles correctly detected, as well as the number of vehicles missed and the number of false detections that occurred in the absence of vehicles. This approach was applied to both passage and presence scoring, but was not possible for speed scoring.

In addition, some direct comparisons to loop detectors were made in locations where a surveillance camera and the necessary detector stations were colocated. This technique will be advantageous in the future, to allow for extensive, automated comparison of WADS performance to that of known detection technology.

Off-line Evaluation in Support of WADS Algorithm Development

This section documents performance of the detection algorithms evaluated across the contents of our two video discs, a 14-minute video disc prepared for the Mn/DOT Phase II contract, and a 30-minute video disc prepared during Task C of this FHWA contract. In all, 50,000 frames of data were processed. The imagery selected for the video disc was extremely variant, containing examples of most of the difficult artifacts, such as shadows, headlights at night, snow, and rain. Results of this off-line evaluation are based on the April 1988 versions of the WADS algorithms.

Intermediate results on this test set steered efforts to improve the algorithms, pointing to where the most significant problems in performance lay. Initially the system yielded up to 10 percent double detections, caused largely by vehicles with a signature that in portions was indiscriminable from the background (characteristic of night data, where the middle of the car is barely illuminated). Results also included up to 20 percent false detections at all times of day, largely caused by changes in illumination of the background that triggered detection: shadows, headlights, and various reflections.

Performance of passage detection was scored by counting the number of cars detected, as well as the number of vehicles detected multiple times (double detections) and the number of spurious counts (false detections). This was done by comparing the detection signal to a ground-truth signal, a manually generated signal that corresponds to the presence or absence of vehicles underneath a detector. It is similar to the signal that would be generated by a loop detector. Figure 7 illustrates the possible combinations of ground truth and automatically generated detection signals. This type of scoring was termed "passage" scoring, because it measured the capability of the system to accurately count the number of vehicles that passed the detector, and ignored the issue of whether the system was detecting vehicles for the appropriate amount of time. For example, a truck at night may only trigger the detector as the headlights pass under, generating a presence signal that is high for only a fraction of the vehicle, yet this would still be considered a correction detection with this approach. It would also be considered a correct detection for a loop-based volume counter, hence the comparison (at least for volume purposes) would be fair.

It should be noted that in subsequent evaluations the number of double detections were not counted separately, and instead were grouped with the false detections. This is largely due to the fact that new improvements to the detection algorithms virtually eliminated all double detections, and it became unnecessary to consider them separately.

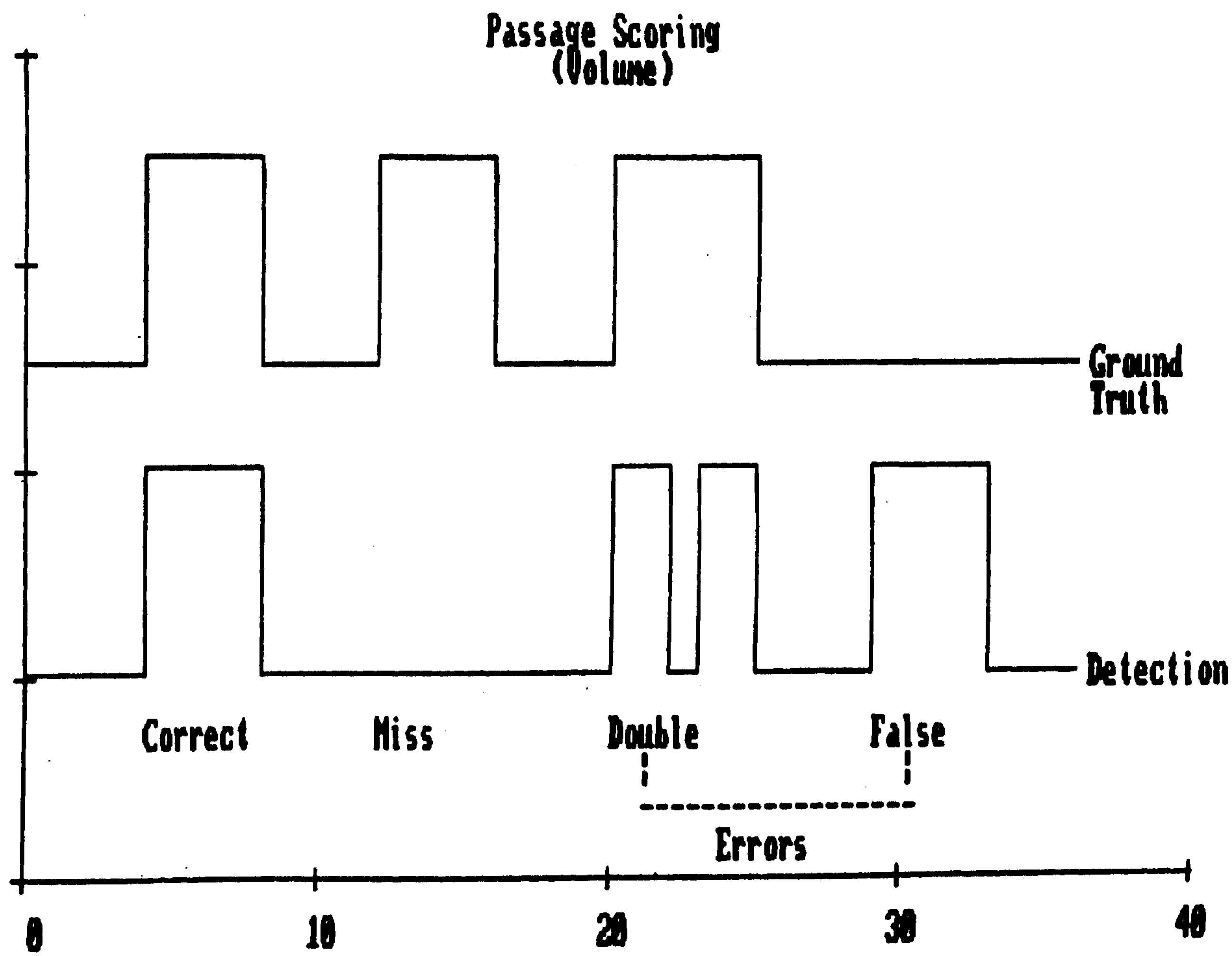


Figure 7. Illustration of passage scoring.

Table 5 summarizes performance of the WADS algorithms on sequences selected from the video discs. Keep in mind that these results were generated in April 1988. Since then the algorithms have undergone extensive on-line evaluation, which has led to further improvements, particularly in nighttime performance (verified in the on-line evaluations presented in following sections).

Table 5. Performance summary of WADS algorithms, April 1988.

Total number of image frames: 51,620
Total number of vehicles: 417

Overall performance	% performance	# vehicles
Detection	93.3	389
Double detection	5.0	21
False detection	8.9	37

Condition	# Vehicles	% Detected	% Doubles	% False
Time-of-Day				
Daytime	229	94.3 (216)	1.3 (3)	3.5 (8) *
Nighttime	95	95.8 (91)	12.6 (12)	22.1 (21)
Dusk/Dawn	93	88.2 (82)	6.5 (6)	8.6 (8)
Artifact				
Shadow	122	95.1 (116)	0.8 (1)	4.9 (6)
Rain	35	100.0 (35)	0.0 (0)	0.0 (0)
Snow	17	88.2 (16)	5.8 (1)	0.0 (0)
Fog	7	43.0 (3)	0.0 (0)	0.0 (0)

* corresponding counts in parentheses

The speed estimation algorithm was also evaluated off-line on the video disc sequences. The evaluation measures used for the performance are percent errors and percent misses. The percent error measure is the comparison of the estimated speed to the actual speed; the actual speed was measured visually by counting the number of video frames it takes the vehicle to traverse the two detectors. The percentage of misses is the percentage of vehicles that did not register a speed measurement (i.e. the algorithm was not able to estimate a speed). The evaluation was performed on the same video data described above. These sequences included vehicles traveling at speeds from 0 (stopped) to 70 mi/h (113 km/h) in all weather conditions during both day and night. The overall error was 12 percent and the misses were 17 percent. These performance numbers are for instantaneous speeds and not average speeds; the average speed performance would improve with the amount of time the instantaneous speeds are averaged.

The majority of the speed estimation errors were due to an insufficient number of samples for vehicles moving at high speed. Since the spacing of the two detectors used for all of these test sequences was 10 ft (3 m), a vehicle traveling at 60 mi/h (97 km/h) traverses a 10-ft (3-m) trap in approximately 4 video frames; this could result in an average estimation error of 25 percent (a 1 frame estimation error). This error can be decreased by increasing the spacing between detectors. For a 40-ft (12-m) detector spacing, error rates of 6 to 7 percent have been measured for vehicles moving at approximately 60 mi/h (97 km/h). In fact, the system's dynamic detector placement capability allows this spacing to be automatically adjusted as the speed estimate changes. The speed estimation misses primarily occurred in sequences with extremely heavy fog (too much noise in the video signal), stopped vehicles (the vehicle reached the first detector but not the second) and sequences in which one of the detectors was in a fixed shadow (from a building) and the other in the sun (this caused poor signal correlation). The speed estimation algorithms were recently improved to deal with these problems and integrated into the real-time system for purposes of performing more extensive on-line evaluation. Preliminary test results obtained as this report was being prepared suggest accuracies in the range of 94 to 96 percent. Finally, the signal correlation technique does not require presence and passage signal extraction and in preliminary testing resulted 90+ percent speed measurement accuracy.

First On-line Evaluation (July 1988)

The first all-day on-line evaluation of the WADS system was conducted on July 7, 1988, running from early-morning pre-rush hour until dusk, at the MnDOT Traffic Management Center. The on-line evaluation was designed to test system performance over the course of typical day.

Two sites were selected, one freeway and one intersection. Two detectors were placed at each site: the left turn lane and center lane of the intersection, and the middle two lanes of a four-lane freeway section. The sites had a north/south orientation in order to maximize the impact of morning and evening shadows from neighboring lanes. Every half hour, from 7 a.m. until 9:30 p.m., the WADS system was run for 5 minutes at each of the two locations. The results were videotaped for archival purposes.

The freeway location was used to evaluate passage (volume) detection to determine how well the system counts vehicles. The intersection was used to evaluate presence (occupancy) detection -- how accurately the system recognizes when vehicles are under the detector. Performance was measured by counting three variables, i.e. the number of correct detections (# detections), the number of missed detections (# missed) and the number of erroneous detections (# errors).

A correct passage detection was defined as a single turn-on of the detection signal that corresponded to a single vehicle. A missed passage detection was a vehicle that passed under the detector without the detector turning on. Finally, a false passage detection was a detector that turned on with no vehicle passing under it.

A correct presence detection was a detector that was on steadily once the majority of the detector was covered by the vehicle and/or the majority of the vehicle was covered by the detector. A missed presence detection was a vehicle that should have turned on the detector (meets the majority criterion) but did not. An erroneous presence detection was a detector that turned on with no vehicle under it.

From these three counts the detection and error rates were derived. First the total number of vehicles was determined, the sum of the total number of detected vehicles and the total number of vehicles missed. Then detection rate was computed as the total number of detections over the total number of vehicles, and error rate was the total number of errors over the total number of vehicles.

Errors due to cross-lane occlusion were ignored, in both freeways and intersections, because as our demonstrations suggest, they can be eliminated with proper camera placement. That is, an occluded vehicle that was not detected will be removed from consideration (# vehicles will not be incremented), and the detection of an occluding vehicle in the adjacent lane was ignored (# false detections will not be incremented). If potential users of the WADS system are interested in applications where it is not possible to optimally place the cameras, it may be more effective to draw conclusions on the impact of cross-lane occlusion from models of traffic distribution and specific viewing geometries than to measure it empirically. Errors due to down-lane occlusion were considered for freeway passage evaluation.

Results from First On-Line Evaluation

Table 6 summarizes the test results corresponding to freeway and intersection sites, averaging across the whole day. Figure 8 shows performance hour by hour, with relative vehicle volume overlaid on the detection rate ("percent Correct") and error rate ("percent Error") plots, for reference in interpreting the figure. The vertical axis is percentage and the horizontal axis is the time-of-day ranging from 07:00 (7 a.m.) to 20:20 (10 p.m.). The maximum number of vehicles in any 5 minute period was 343 at 7:30 a.m. on the freeway.

The intersection results show stable performance across the entire day with a few stretches of increased error rate. The increased error rate at 8:30 was due to camera motion -- gusts of wind repeatedly blew the detectors across a painted stripe on the road, triggering detection. The increased error rate at 17:30 was due to a combination of wind motion and building shadows creeping across the detectors.

Table 6. Mean performance during first on-line evaluation.

	Freeway	Intersection
% Correct	91.8	98.5
% Error	2.3	5.1

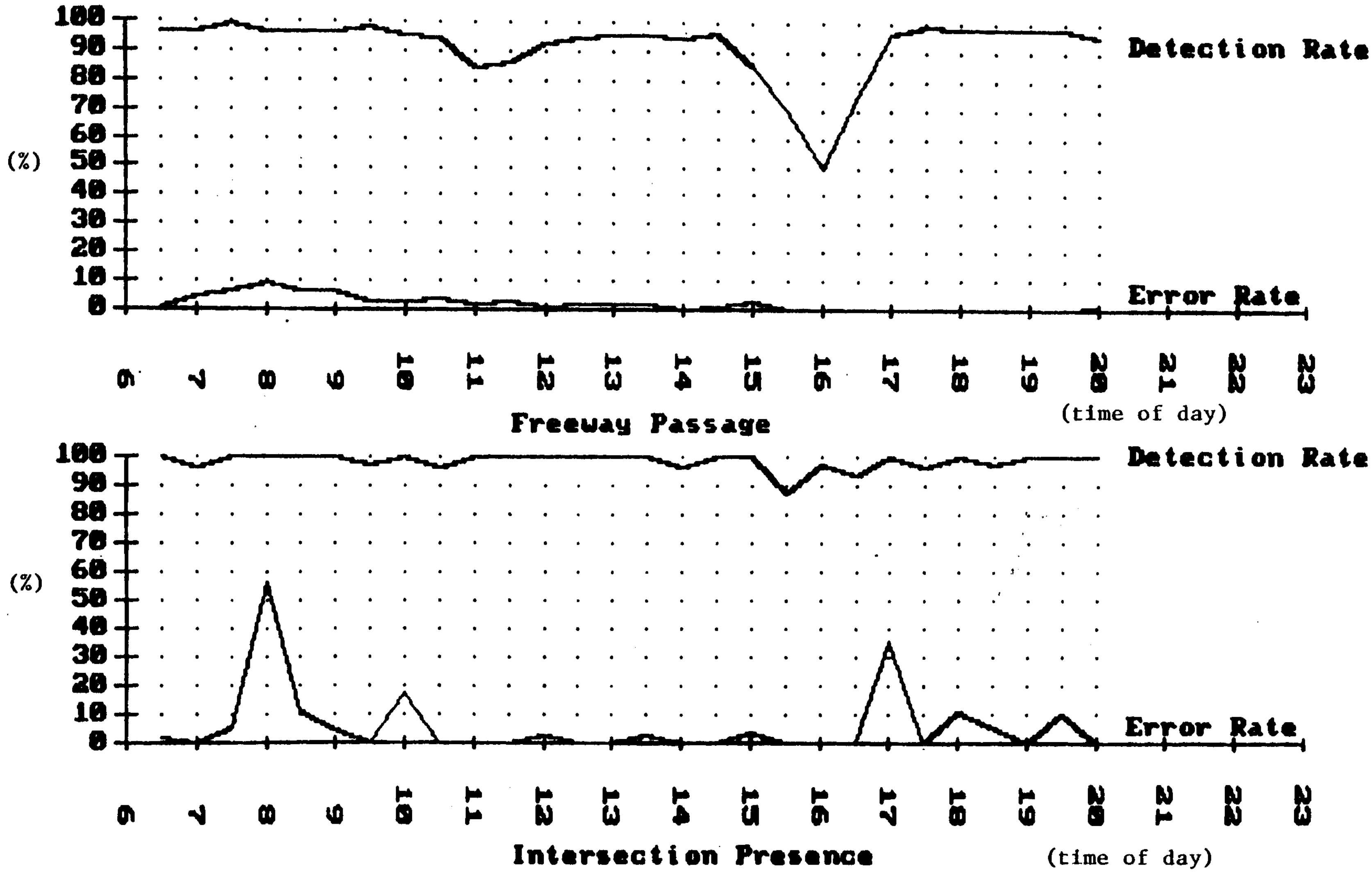


Figure 8. First WADS all-day performance, July 7, 1988.

The freeway results illustrated two problems areas: shadows and congestion. Shadows from adjacent lanes were present under the detectors from 7:00 until almost noon. At 9:00 the shadows were the main cause of an error rate of 30 percent. These stemmed largely from the downlane detector of the pair of detectors placed on each freeway lane. At all times there were a greater number of shadows correctly avoided than shadows that were counted in error. Figure 9 depicts the number of shadows that could potentially cause an error compared against the number of errors in the passage count, from 7:00 until 10:00. At 7:00 only 1 out of 15 shadows was counted in error. At the worst time, 9:00, one out of two shadows was correctly avoided.

During afternoon rush hour, an incident that blocked traffic occurred at approximately 15:30. This significantly reduced the volume of traffic on the freeway and the resultant congestion reduced the detection rate (% Correct) to as low as 50 percent at 16:30. A brief rainstorm at 17:00 did not result in any reduced performance.

Transitioning to dusk (at 20:00 and 20:30) did not result in reduced performance until illumination fell too low for the fixed iris cameras being utilized. At 21:00 noise dominated the image in both cameras, and video from the intersection camera would tear as headlights traversed it.

Conclusions from First On-Line Evaluation

This first all-day on-line evaluation represented a major step in the design and development of the WADS system. This was the first time we observed system performance on a fixed installation of detectors over an extended period of time and conditions. It illustrated how performance was generally adequate over the majority of the day, with some problems that needed addressing. After this the research team proceeded to

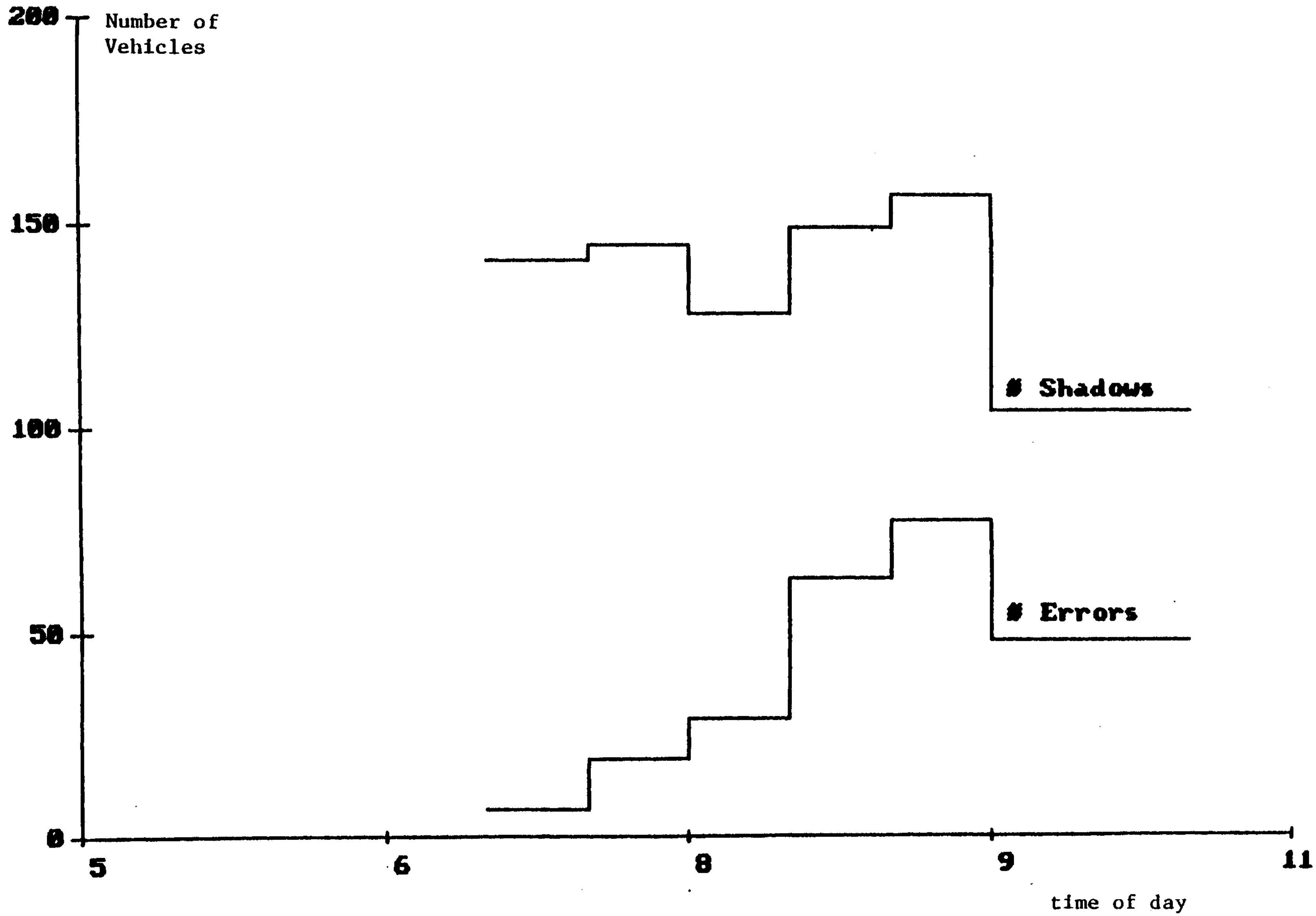


Figure 9. Performance in presence of shadows, July 7, 1988.

"flatten" out the performance curves by tackling the specific problems the evaluation uncovered.

First, it was determined that the basic approach used for shadow avoidance was sound, and that the problems encountered around 10:00 a.m. could be addressed by tuning of the algorithmic parameters, and perhaps further experimentation with detector structure and placement. This in fact proved to be the case in the January 1989 on-line evaluation.

Next, it was determined that the technique used to estimate the profile of the freeway road-surface was not designed to handle occupancy beyond a certain percentage (approx. 30 percent), i.e. congestion. This became apparent during the incident-induced congestion encountered during the on-line evaluation, where detection performance dropped to as low as 50 percent Prior to the second on-line evaluation, the research team refined this technique to operate at times of greater congestion, allowing for accurate presence detection under all traffic flow conditions, and accurate passage detection up to the point where vehicles are merged due to down-lane occlusion. This was then validated in the January 1989 on-line evaluation.

Problems due to wind motion may be addressed through the use of smaller, more aerodynamic camera housings (the one used was an older, bulkier design with approximately 3 ft^2 (1 m^2) "sail" area). Discussions with camera operators in European cities where such compact cameras are now installed support this conclusion. In the event of extreme wind conditions, camera motion can be handled by tracking the sway of the video imagery and shifting the detectors to compensate. Currently every other field of video (1/60th of a second) is not utilized. The video data available in this time slice could be exploited to estimate the translation of the image due to wind using correlation techniques. This would require the addition of a vector coprocessor to perform the necessary calculations, as well as software and hardware development necessary to support dynamic positioning of detectors.

Second On-line Evaluation (January 1989)

The second all-day evaluation of the WADS system was conducted on Friday, January 27, 1989 at Mn/DOT's Traffic Management Center. System performance was sampled for 10 minutes out of each half-hour, starting prior to sunrise (6:30 a.m.) and proceeding until after sunset (6:00 p.m.). The goal of this evaluation was to measure improvements to system performance since July 1988 (the last all-day evaluation), and at the same time assess performance during the dawn and dusk rush-hours that occur during late fall and early winter. Due to the Mn/DOT camera placements, it was decided to concentrate this evaluation on freeway data. None of the cameras are placed ideally for intersection detection nor close to heavily traveled intersections. Two video-based detectors were placed on the second and third lane of southbound 35W just north of the 42nd street overpass in Minneapolis. Performance of the system was tabulated with a manual count of the correct, missed, and erroneous detections in the same manner as the July 1988 on-line evaluation.

Table 7 compares the results from this all-day evaluation to the results of the July 1988 evaluation. A more complete picture of performance improvement is given in figure 10. The top line in each graph is the detection percentage, and the bottom line is the error rate. Detection performance improved 1.4 percent and the error rate dropped by half a percent. Most importantly, performance was far more consistent across the course of the entire day than during the July 1988 evaluation, especially with respect to error rate.

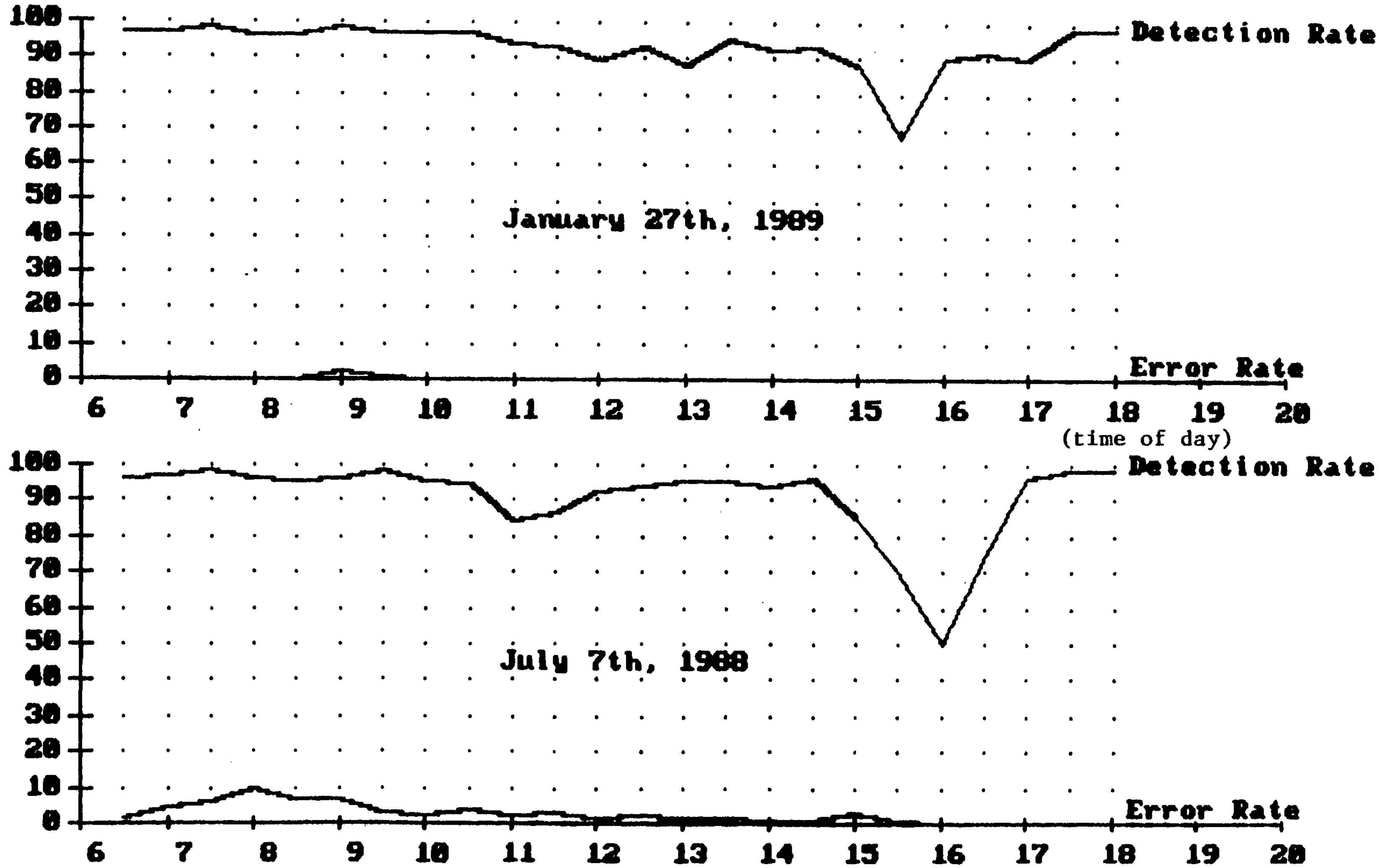


Figure 10. Improvement in WADS all-day performance.

However, once again the on-line evaluation was able to highlight problems with system performance that had been previously overlooked. The detection percentage (93.2 percent) was not optimal during this recent all-day evaluation for two different reasons. First, the placement of detectors was not ideal, causing vehicles to overlap one end of the detector. This presented a problem on vehicles of low contrast, causing the system to not count them. Thermal expansion of the camera mounting aggravated the problem over the course of the day, as the detectors drifted farther and farther from an ideal location. Up to 1 out of 10 vehicles were missed in any half-hour period due to this problem, which can most likely be corrected by better detector placement.

Table 7. Improvement in results of on-line evaluation

	%Detection	%Errors
Jan. 1989	93.2%	1.8%
Jul. 1988	91.8%	2.3%

A second reason was responsible for the detection percentage falling far below 90 percent, around 3:30 p.m.. At this time of day the detectors fell within the mottled shadow of a nearby tree. The strength of signals collected from vehicles in the shadow were judged insignificant by the algorithms, when in fact it would have been a simple matter to separate these vehicles from the background if the significance level was better adjusted. However, in other imaging conditions we have encountered, the strength of the signal from the shadowed vehicles would have been in the noise, and a lower setting of the significance level would result in a much higher error rate. We are currently improving the technique employed for the setting of the significance level, in order to improve the adaptation to different imaging conditions.

The system ran continuously for 24 hours, it had been installed and initiated at Traffic Management Center (TMC) the previous evening. In this manner the algorithms, software, and hardware have now been demonstrated in around-the-clock operation.

Laboratory Evaluations

During the second on-line evaluation, the video detectors had been placed in close proximity to an existing detector station on southbound I-35W. After the on-line evaluation, the actual 5-minute loop volumes and occupancies for this detector station were dumped from the TMC computer. In the laboratory the following week, the system was rerun on videotapes that had been collected simultaneously during the on-line evaluation, and the volume and occupancies (5-minute averages) output by the WADS system were compared with those collected from the detector station. This was done for a 2-hour period from 16:00 to 18:00. This period was chosen because of the relative difficulty of conditions: congestion, vehicle shadows, tree shadows, and transition to dusk.

Figure 11 compares loop generated volumes to WADS generated volumes, one plot for each lane. The accuracy of the volume count increased as the sun set around 17:30. Figure 12 compares loop generated occupancies to WADS generated occupancies. It demonstrates the need for an adjustment to occupancy measures as the sun sets.

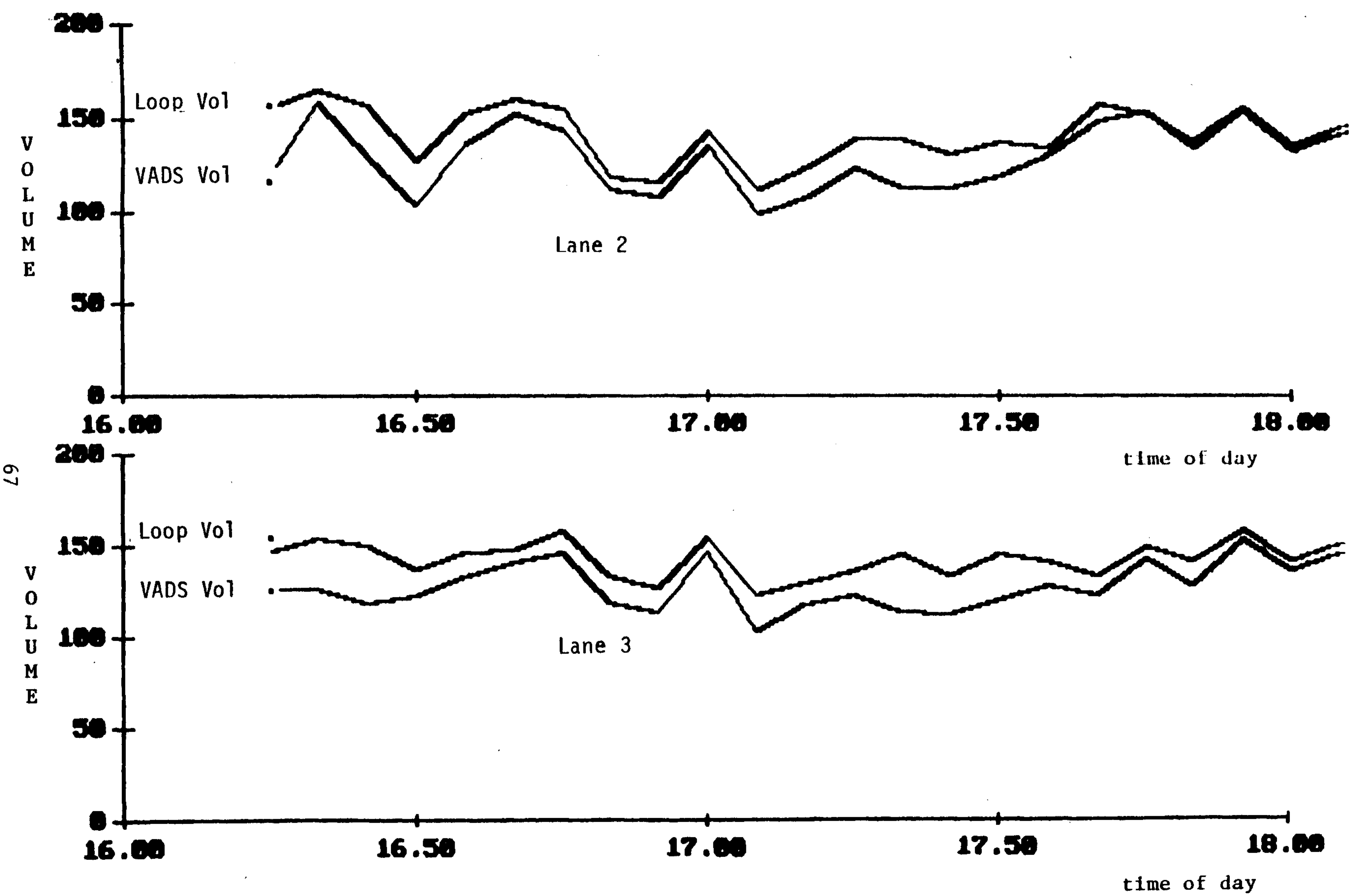


Figure 11. Comparison to loop generated volumes.

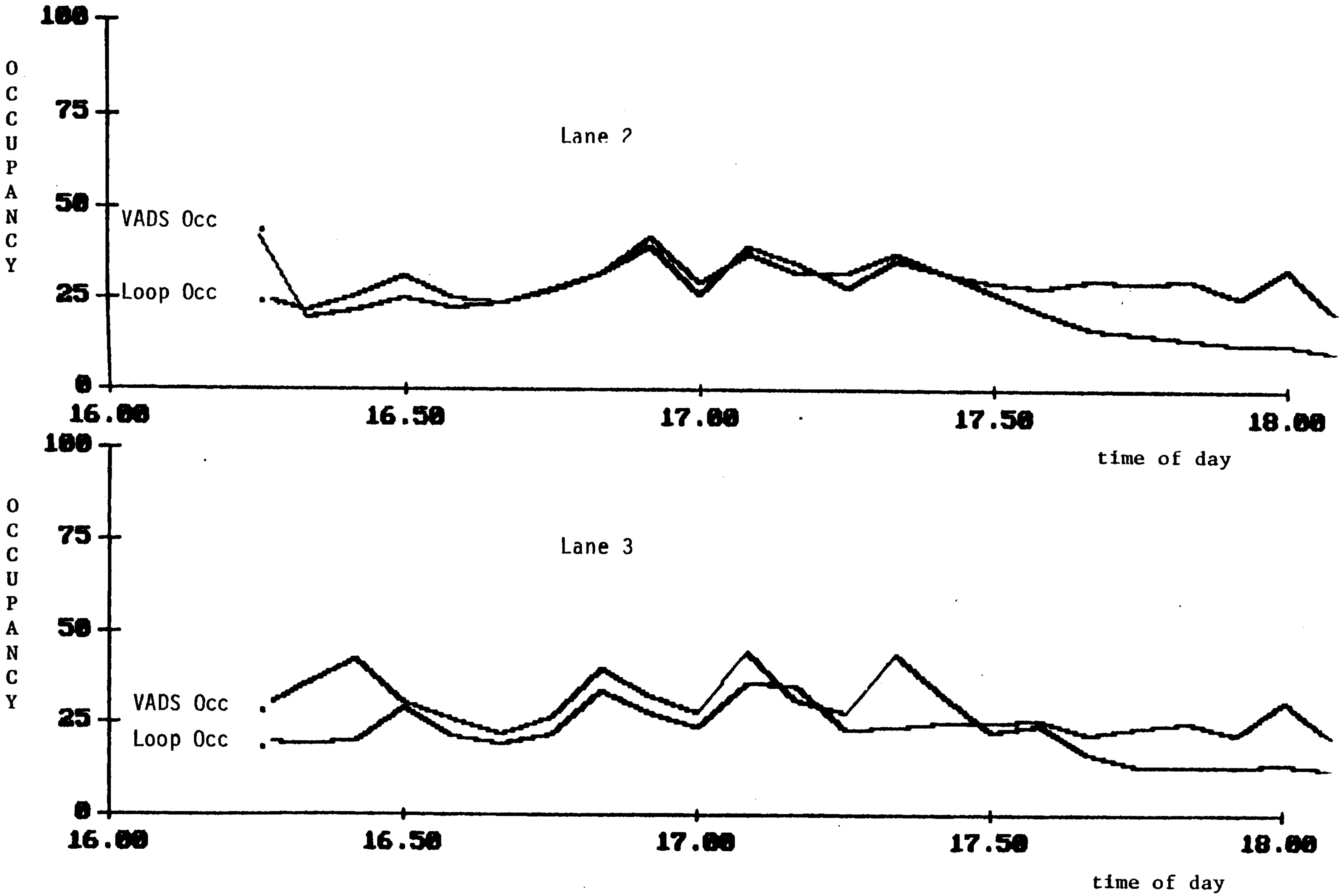


Figure 12. Comparison to loop generated occupancies.

A more complete comparison of WADS performance to loop performance was conducted.[29] In this effort both the loop and WADS generated measures were compared against a manually generated ground-truth. This effort also evaluated the accuracy of higher level traffic parameters such as total travel and total travel time.

Overall results are summarized in table 8, showing the range of accuracies found at the six different testing locations. Over 8 hours of video data was processed. Evaluations were done under light, medium, and heavy traffic flow conditions, with some occurrence of stationary and moving shadows.

Table 8. Overall evaluation of WADS performance at six different sites.

Traffic Measure	Accuracy %
VOLUME	92.19 - 98.32
SPEED*	94.57 - 97.66
TOTAL TRAVEL	90.76 - 96.06
TOTAL TRAVEL TIME	92.08 - 97.21

* the speeds measured were in the range 40 to 65 mi/h (64 to 105 km/h).

The speed, total travel, and total travel time, were evaluated by comparison to speeds collected by a radar detector

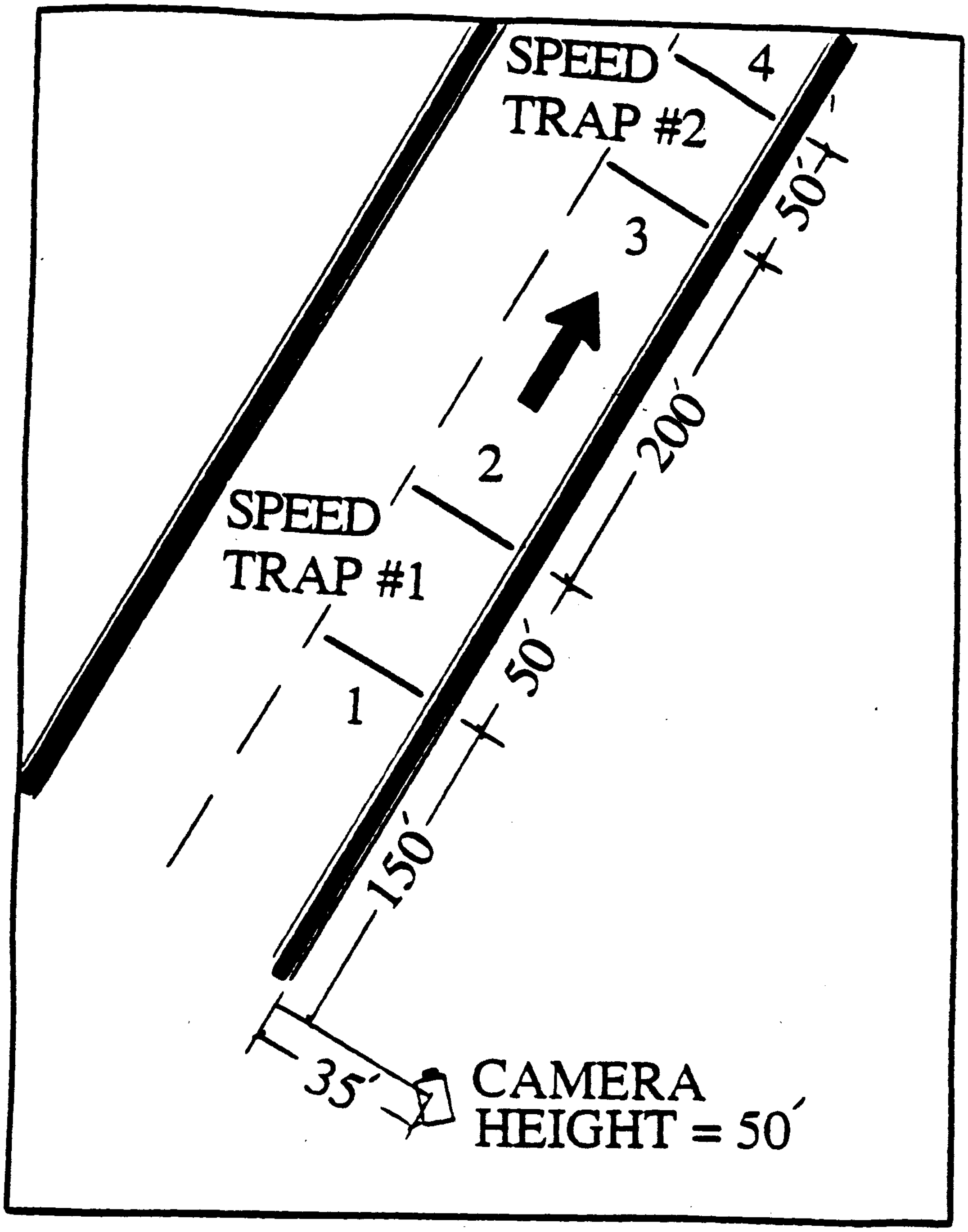


Figure 13. Test site #2: comparison of WADS speed detection to radar detection.

temporarily set up in the field. For example, at test site #2, shown in figure 13, two speed traps were constructed in lane #1, each trap 50 ft (15 m) in length, separated by 200 ft (61 m). A radar detector was mounted downlane from each speed trap. The results for test site #2 are summarized in table 9.

At test site #6, shown in figure 14, the output of the WADS system was compared to the output of a colocated loop detector, at two different times of day. Both were contrasted to manually entered volumes. Results are shown in table 10. It is worth noting that in this test case the WADS system actually out-performed loops.

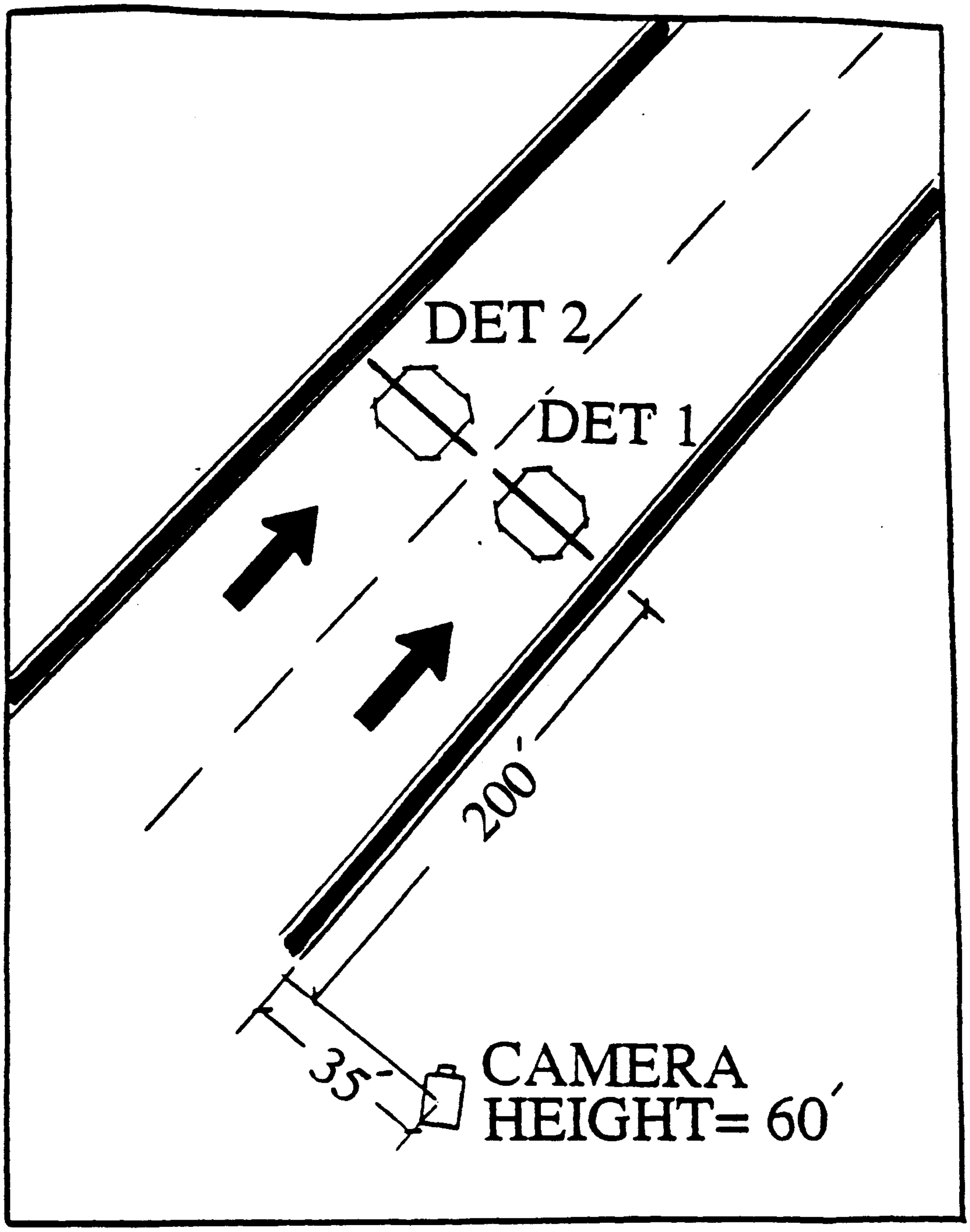


Figure 14. Test site #6: colocated WADS and loop detectors.

Table 9. Test site #2: comparison of WADS traffic parameter estimation to radar-based measures.

Traffic Measure	Accuracy %	
	5-Minute Interval	Overall
VOLUME		
Detector #1	93.24 - 99.92	95.73
Detector #2	94.59 - 99.06	96.77
Detector #3	89.38 - 98.20	94.87
Detector #4	88.87 - 97.14	93.72
SPEED*		
Trap #1	93.47 - 99.87	96.90
Trap #2	92.83 - 99.93	97.14
TT	92.42 - 99.27	95.39
TTT	88.21 - 98.65	95.02

* the speeds measured were in the range 40 to 65 mi/h (64 to 105 km/h).

Table 10. Test site #6: comparison of WADS performance to loops.

	Accuracy %	
	WADS	Loops
I. (7:45 - 8:55)		
Detector #1	97.12	97.72
Detector #2	98.38	97.16
II. (15:25 - 16:55)		
Detector #1	98.57	97.16
Detector #2	96.99	95.46

9 WADS SPECIFICATIONS AND FUTURE WORK NEEDS

The practical applications of WADS are many. The main advantages lie in the employment of cameras that allow multiple wireless detection and the fact that such a system is essentially a wide area detection device. Therefore it should not be viewed simply as a replacement of loops, which will continue to serve their intended purpose for a while, but rather as a device that leads to new potential applications which, due to cost and complexity, could not be attempted with existing hardware. In addition, the real-time WADS video detection system can quickly be installed or connected to existing cameras for multi-spot wide-area detection without disruption of traffic operations. Another important consideration is its ability to perform several functions simultaneously. Multiple functions include incident detection, control, surveillance, counting/classification, traffic parameter and MOE extraction, and bus and special vehicle recognition. These functions can all be performed simultaneously.

Despite its good performance, the WADS system currently is not a production line prototype. Most importantly, it has not as yet been tested in the field over a sufficiently long time period to demonstrate its long-term robustness and reliability. Without such testing the technology is unlikely to gain the confidence and trust of practicing engineers. This confidence would further erode with the premature product introductions abroad (section 3). To be sure, the enthusiasm and support gained to this point will evaporate if introduction of the technology in the field is not deliberately followed through with further work. Naturally, the industry should also be involved in the productization stage, but the system is unlikely to create serious interest without field applications and demonstrations.

Based on these simple observations, this section presents the specifications and design of the current and a desirable WADS system, its throughput capabilities and recommendations on additional work that needs to be performed for keeping the technology alive. Finally, a few of the most exciting WADS applications suitable for demonstration projects are presented.

WADS Specifications

A fieldable real-time system that implements the WADS algorithms is a much smaller, less expensive and more self-contained device than a desktop computer. It is essentially an industrial personal computer. The primary reasons for choosing an IBM-PC-AT-compatible system were the low cost and high availability of software and peripheral hardware (e.g. video digitizers), the high throughput of the processors, the excellent software support and the dedication to remain generation-to-generation software compatible. For instance, the system is fully compatible with the newer INTEL 80386 based machines (both desktop and industrial) even though initial development began on an IBM PC based on the 8088 microprocessor.

The real-time fieldable system envisioned is shown in figure 15. The system is equipped with a real-time video digitizer and formatter which accepts video from any standard video source (American or European) and converts the video into a digital format that can be utilized by the microprocessor. The video source for a fieldable system originates from a camera mounted along the road on a dedicated pole. Alternately a camera can be mounted on existing structures such as lighting standards, surveillance poles, sign masts, bridges, or buildings. The real-time system can also be installed at a central surveillance location with real-time video brought in from cameras (via CCTV) in the field or in an office using a VCR as a video source. A keypad or mouse is connected to the system with a video output

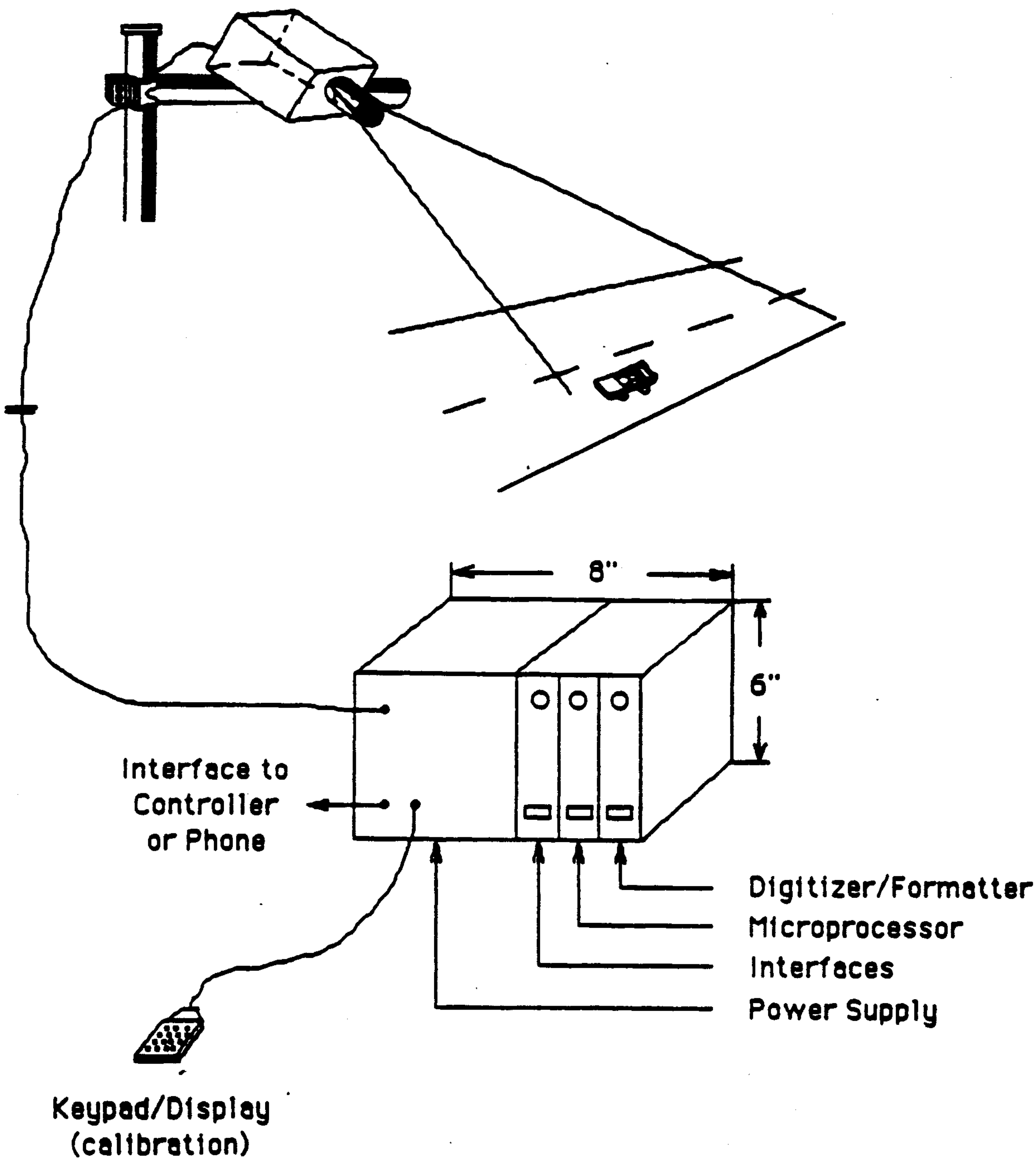


Figure 15. Real-time fieldable system.

display for installation (detector placement and calibration). The same functionality can also be accomplished from a central surveillance location by getting the video image from the field (compressed image transmission or multiplexed CCTV) to a workstation. The detector placement and calibration are performed on this dedicated workstation (personal computer with video display capabilities). The placement and calibration information are then transmitted back to the field over standard serial communications (twisted pair or telephone).

Proper system installation and operation is verified immediately after installation using the video output display. The video output displays the video images from the camera overlayed with graphical information. The graphical information consists of the detection spots selected for the installation. After the system is installed the video output display is used to visually verify that the system has been properly installed.

The detection information (presence, passage, and speed) as well as other traffic parameters are sent back to the central control by standard serial communications over twisted pair or telephone. The communication bandwidth requirements are similar to those of controllers currently used in the field.

The original WADS system specifications detailed are presented in table 11. The system currently meets or exceeds these specifications.

Table 11. Current real-time specifications.

range:	500 ft (152 m)
coverage:	4 lanes
detectors:	10 detectors
cameras:	1

For the system to be truly cost effective in fieldable applications, a more extensive set of specifications, shown in table 12, has been compiled from discussions with the many engineers and other traffic operations personnel that have been exposed to WADS technology in presentations and real-time demonstrations:

Table 12. Suggested future WADS real-time specifications.

range:	1000 ft (305 m)
coverage:	6 lanes
detectors:	60 detectors
cameras:	upto 4, handled by the same device

These specifications can be met by extending the capabilities of the various components of the WADS architecture. The possible number of detectors can be increased, first by further optimization of the algorithm implementation, then by the addition of numeric coprocessors, based on either INTEL 80386 architecture or alternate technologies such as the INMOS transputer. The number of lanes to be covered is a function of height and camera field-of-view, not necessarily a question of the system's processing capabilities. Support of multiple cameras can be accomplished by the addition of extra digitizer/formatter processing units, one set for each two cameras.

The most difficult specification to meet may be the extension of range to 1000 ft (305 m). The problem lies in the difficulty of detecting individual vehicles at ranges where vehicles closer to the camera partially occlude vehicles more remote. We need to investigate extensions to the existing WADS algorithms based on signature analysis and edge recognition techniques that will have the potential of separating partially occluded vehicles.

Traffic Parameter Derivation

The main advantage of WADS is its ability to simultaneously perform multiple functions at a lower cost (since it can replace many loop detectors) while having the capability of deriving more traffic parameters than loops. For the reasons described earlier, traffic parameter derivation was not performed in this project but it is at the top of the priority list for ongoing research through various funding sources as they become available to the research team. If additional funding is approved shortly after the preparation of this report, as expected, then on line traffic parameter software utilizing the output of the WADS system should be available in summer 1989. This software, in addition to the traffic parameters described here will also extract the most widely used measures of effectiveness (MOE's) employed in practice. Such MOE's include: total travel, total travel time, stops, delays, and energy consumption. With this additional software the WADS system can also be used as a real-time evaluation device for assessing the effects of improvements (i.e., in signal timing, reconstruction project, etc.). Naturally, the remaining traffic parameters derived by WADS can be utilized for control and surveillance purposes.

This section presents the theory that will be utilized for extracting the most common traffic parameters from WADS. As one might expect, derivation of these parameters depends on the placement of the detection lines in the image received by the camera. Table 13 presents possible detection line placements in a two-lane area for deriving the required traffic parameters. As the table suggests, multiple detection is required for extracting all parameters.

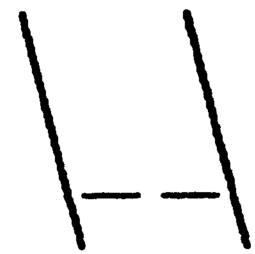
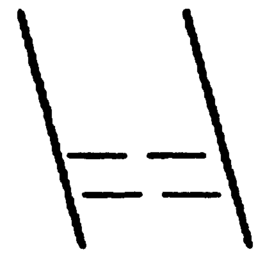
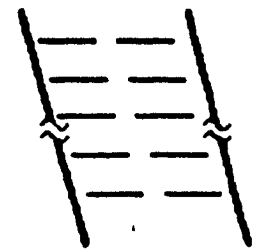
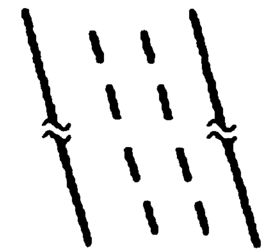
Traffic Parameter / Placement				
PRESENCE Point	X	X	X	X
Area			X	X
SPEED		X	X	X
LANE DIST	X	X	X	X
VOLUME	X	X	X	X
STOPS			X	X
DELAY		X	X	X
HEADWAY	X	X	X	X
QUEUE			X	X
PLATOON PROFILE	X	X	X	X
OCCUPANCY Time	X	X	X	X
Distance			X	X

Table 13. Possible WADS detection line placements for traffic parameter extraction.

Definition of the traffic parameters along with their most important application, and their method of manual measurement from video data is presented in table 14. In summary, these parameters are needed primarily in traffic control and incident detection; however, they can also be employed in other applications of the WADS system such as counting/classification, surveillance, preparation of data for signal network design and analysis packages (i.e., NETSIM, TRANSYT 7F, etc.) off line system evaluation safety analysis, etc.

From the presence/passage signals and vehicle speed measurement which we are currently developing in the ongoing Mn/DOT project, it is possible to derive all the traffic parameters required in practice. This is of crucial importance since it reduces the need for additional image processing development and promotes a more flexible system design.

Following vehicle detection over a detection line (or station) and measurement of the individual vehicle speeds over each station, measurement of the traffic parameters can easily be derived by WADS software. The following discussion presents the formulas referring to either a single detection line or a segment in the WADS area to illustrate how the required traffic measurements can be derived from presence and speed data. Extension for the entire WADS area can easily follow. Referring to figure 16 define:

s = the station (detection line) number;

S = the total number of stations;

n = the vehicle number passing over a station;

ℓ = the lane number;

L = the number of lanes;

Δx_s = the spacing between station s and s+1;

T = the number of scanning intervals having duration Δt;

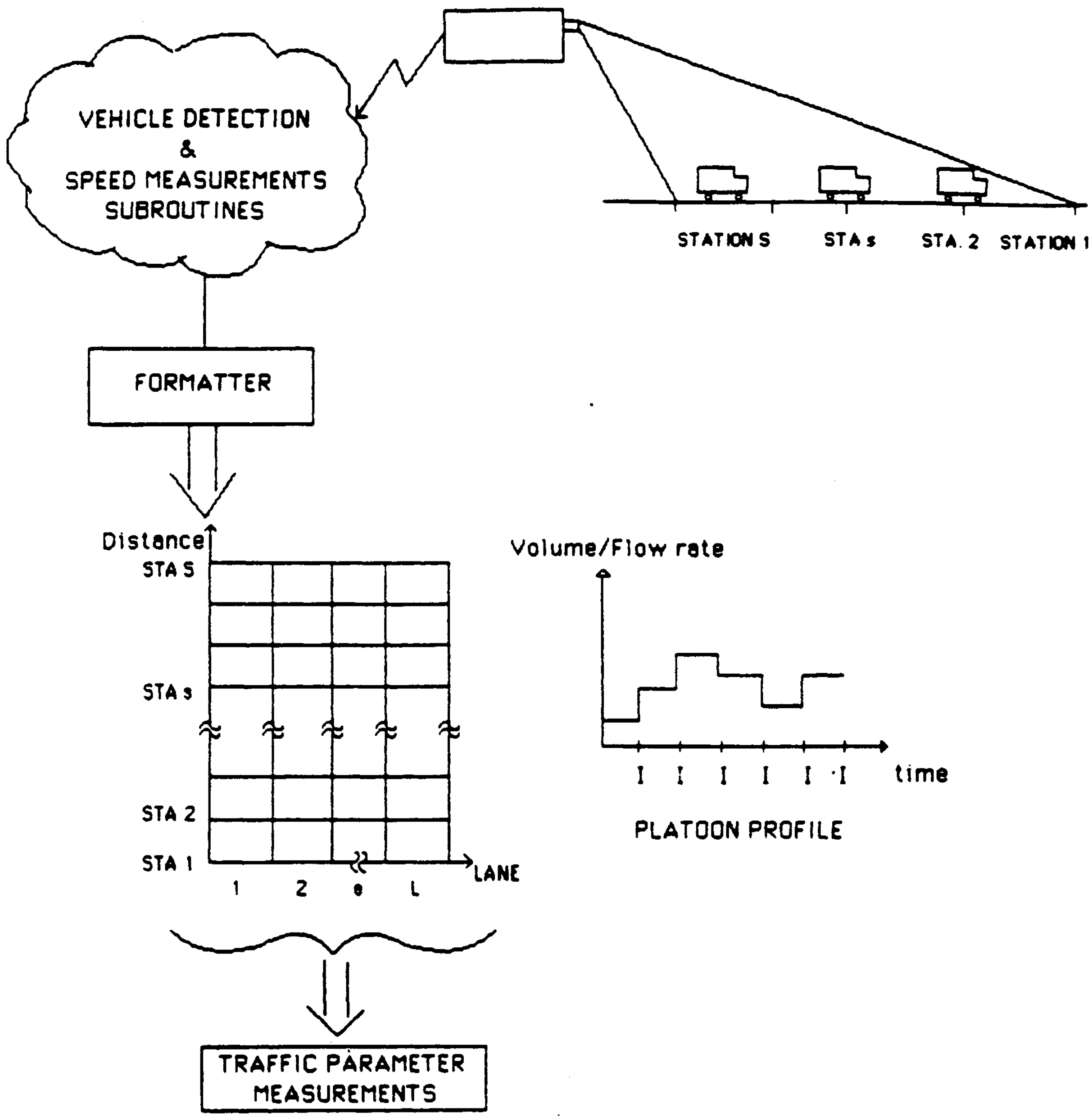


Figure 16. Derivation of traffic parameters from WADS detection.

$t_{s\ell n}$ = the time at which the nth car in lane ℓ arrives at station s;

$v_{s\ell n}$ = the speed of the nth car at station s line ℓ;

$Q_{s\ell}$ = the volume at station s line ℓ over period $T \cdot \Delta t$;

Q_s = the total volume over all lanes at station s.

From the above notation the time mean speed at station s line ℓ is:

$$V_T = \frac{\sum_{n=1}^{Q_{s\ell}} v_{s\ell n}}{Q_{s\ell}} \tag{1}$$

and over all lanes at s:

$$V_T = \frac{\left(\sum_{\ell=1}^{L} \sum_{n=1}^{Q_{s\ell}} v_{s\ell n} \right)}{Q_s} \tag{2}$$

The space mean speed is:

$$\overline{V} = \frac{\Delta x_s}{\text{Av. Travel Time}} = \frac{Q_s \, \Delta x_s}{\sum_{\ell=1}^{L} \sum_{n=1}^{Q_{s\ell}} \left(t_{(s+1)\ell n} - t_{s\ell n} \right)} \tag{3}$$

Table 14. Summary of traffic parameter definitions, applications, and manual extraction.

PARAMETER	DEFINITION	APPLICATION	MANUAL MEASUREMENT
PRESENCE	Identification of the existence of a vehicle in the vicinity of a point or within a section of roadway	* Demand at a traffic signal * A base attribute used to derive other parameters * Vehicle actuated control	Established directly by visual observation
SPEED	1. Distance travelled by a vehicle per unit of time 2. May be averaged over a sampling period as a time mean speed or space mean speed	* Incident detection and surveillance * Safety analysis * Progression design * Performance evaluation of delay studies * Speed, TT and delay studies	1. measurement of travel times for individual vehicles over a known distance 2a. Determine total travel distance from volume*length of section 2b. Determine total travel time by integration of vehicle storage 2c. Divide total travel distance by total travel time
LANE DISTRIBUTION	Proportion of traffic volume recorded in each lane	General traffic flow description. Incident detection. High way capacity and geometric design calculation	Requires a lane by lane volume count
VOLUME	The number of vehicles passing a point per unit of time	Vehicle counting. Estimation of demand. Estimation of traffic stream momentum. Signal timing. Planning	Traffic count by observation

Table 14. Summary of traffic parameter definitions, applications, and manual extraction (continued).

PARAMETER	DEFINITION	APPLICATION	MANUAL MEASUREMENT
STOPS	Reduction in speed below a specified threshold value (e.g. 5 mph)	* Performance evaluation (quality of flow) * Energy consumption estimation	Direct speed measurement for individual vehicles
DELAY	1. Stopped delay accumulated in vehicle sec. 2. Excess travel time accumulated when speed drops below desire speed.	* Performance evaluation * Some potential for delay minimization for on-line signal control	1. Accumulation of stopped delay by manual observation 2. Computation from measured speed and volume
HEADWAY	Elapsed time between the beginning of two successive presence detections	* Determination of flow rates * Analysis of headway and GAD distributions * Actuated control * Ramp control	Requires frame count between successive vehicle arrivals at a specified point
QUEUES	Successive chain of stopped vehicles	Performance evaluation, Incident detection, Freeway ramp metering, Signal control	Count of queued vehicles by observation

Table 14. Summary of traffic parameter definitions, applications, and manual extraction (continued).

PARAMETER	DEFINITION	APPLICATION	MANUAL MEASUREMENT
PLATOON PROFILE	Histogram of arrival rates per unit of time throughout a signal cycle	* Traffic signal progression evaluation * A calibration factor for TRANSYT-7F * Signal coordination	Requires frame by frame accumulation of vehicle arrivals to construct histogram
OCCUPANCY	1. Cumulative presence time as a proportion of the sampling period. 2. Proportion of a given roadway length occupied by vehicles.	Used as an estimation of traffic density	Requires a frame by frame accumulation of presence

or alternatively:

$$\bar{V} = \frac{\text{Total Travel}}{\text{Tot. Trav. Time}} = \frac{Q_s \, \Delta x_s}{\int_0^{T\Delta t} N_{st} \, dt} \qquad (4)$$

where N_{st} represents the number of cars in Δx_s at time t, which can be obtained from longitudinal detection.

The value $Q_{s\ell}$ during a time period $T\Delta t$ is easily obtained from the number of presence signals at station s line ℓ. Thus $P_{s\ell t}$ represents presence on station s line ℓ at time t then $P_{s\ell t}$ = 0 when there is no car over station s line ℓ and $P_{s\ell t} = 1$ otherwise. The volume $Q_{s\ell}$ will be incremented whenever the Boolean condition:

$$P_{s\ell t} \cdot [P_{s\ell T} \oplus P_{s\ell (T-1)}] \quad (5)$$

is met. Stated otherwise the total volume over the sampling period will be the accumulation of individual vehicle actuations (counts). Flow rate (in vehicles/unit time) is easily derived by dividing volume over the sampling period. Naturally, the volume entering and leaving the WADS area is the volume measured over all lanes at the first and last station respectively.

Lane distribution is also simple to obtain from volumes by calculating the ratio of the lane volume over the total volume. For instance, the lane distribution at station 1 lane 1 is:

$$D_{11} = \frac{Q_{11}}{Q_1} = \frac{Q_{11}}{\sum_{\ell=1}^{L} Q_{1\ell}} \quad (6)$$

Measurement of stops is obtained from speed by setting a lane stop flag whenever it is determined that the speed at a detection station in the lane has fallen below a threshold value. The number of stops should be incremented whenever a vehicle enters the WADS detection area in a lane in which the stop flag is set. The lane stop flag must be reset whenever no stop is detected at any station in the lane.

Delay can be obtained from both presence (occupancy) and speed. More specifically Stopped Delay is measured by setting a threshold value t_o for vehicle presence at each station. This value constitutes zero delay in terms of an integer multiple of Δt. Stopped delay is incremented by Δt for each scan interval with vehicle presence exceeding t_o. Travel delay can be measured by defining a reference speed threshold v_o which represents the desired speed through the detection area. Then the individual vehicle delay $d_{s\ell n}$ measured from the speed at station s is:

$$d_{s\ell n} = \min\{(\frac{\text{WADS Area Length}}{v_{s\ell n}} - \frac{\text{WADS Area Length}}{v_o}), 0\} \qquad (7)$$

and the total area travel delay is:

$$\text{Tot. Area Delay} = \sum_{\ell=1}^{L} \sum_{n=1}^{Q_{s\ell n}} d_{s\ell n} \qquad (8)$$

The time headway $H_{s\ell n}$ can be determined directly from the start of successive presence signals from:

$$H_{s\ell n} = t_{s\ell(n+1)} - t_{s\ell n} \qquad (9)$$

where $t_{s\ell n}$ is the time of arrival of the nth vehicle in line ℓ at station s. Although it is not required, space headway $H'_{s\ell n}$ can also be measured from:

$$H'_{s\ell n} = H_{s\ell n} v_{s\ell n} \qquad (10)$$

Headways may be accumulated over the sampling period to determine average values or they may be accumulated by class interval (integer multiple of Δt) to generate a histogram.

For generating platoon profiles an interval I must be defined as an integer multiple of Δt. The cycle length must be an integer multiple of I. Then the total volume (or flow rate) at any station and lane may be subdivided into a histogram as shown in figure 16. In short, platoon profiles are really a graphical representation of volumes or flow rates in time and space (stations) and do not require any special algorithm development.

Queue measurement requires contiguous closely spaced detection stations or longitudinal detection lines. The queue length is defined in terms of the furthest upstream detection station with a stopped vehicle detected. The latter requires only speed measurement, i.e., again no special image processing algorithm is required for queue length measurement.

Finally, occupancy is determined from the presence signals generated at each station. If $P_{s\ell n}$ is the binary representation of presence as defined earlier, then the area occupancy accumulated over T scanning intervals of Δt seconds is:

$$O = \text{Area Occupancy} = \{ \sum_{s=1}^{S} \sum_{\ell=1}^{L} \sum_{t=1}^{T} P_{s\ell t} \} / (SLT) \tag{11}$$

It should be evident that occupancy over a lane or a single station is a special case of the above equation. For instance, occupancy in lane 1 station 1 is:

$$O_{11} = \sum_{t=1}^{T} P_{11t} / T \tag{12}$$

for the entire station 1.

Additional Testing and Validation

For the reasons mentioned earlier in this section, it is important to test and validate the system in the field over a sufficiently long period of time to ensure its robustness and reliability in future applications and to identify unexpected problems as well as fine tune and calibrate. In addition to testing and validation, a number of other important objectives can be accomplished. First, demonstrate that WADS can be used as a mainline detection station in a loop replacement application.

Second, familiarize traffic engineers in the use of the system and build their confidence in its capabilities, performance, and potential applications. Third, obtain feedback for improving the design of the system to encourage its widespread use in advanced traffic monitoring and control applications. Finally, complete the most important task that was not finished in this project for the reasons presented earlier, namely derivation of traffic parameters.

The tasks to implement the testing and validation should include: site selection/installation design, WADS system procurement, automated evaluation system development, WADS system installation and evaluation, WADS algorithm enhancement, WADS range extension, and traffic parameter derivation/database generation.

Task 1: Site selection/installation design. Sites that differ in physical geometry, traffic composition, and traffic density should be selected in this task to completely exercise the WADS system. The sites should be designed also to allow the determination of tradeoffs in accuracy due to mounting height and to camera positioning with relation to the road. Ideally, these locations would also have loop detectors that can be colocated with WADS detectors in order to perform direct comparisons.

Task 2: WADS system procurement. A real-time WADS system would need to be fabricated for each selected site. Additionaly, if unattended, automated evaluation is desired, each real-time system would require equipment that would allow the selective and automatic cataloging of WADS and loop detection information as well as the associated video.

Task 3: Automated Evaluation System Development. The purpose of this task is to reduce the amount of tedious labor intensive work that is necessary to fully test a field installed

WADS system. Automated evaluation would allow unattended WADS system validation and evaluation over long time periods, thus compiling a complete performance database, even during periods when the weather is too poor to allow personnel to travel to the WADS installation.

Task 4: <u>WADS system installation and evaluation</u>. This task simply involves the installation of the equipment necessary to allow WADS real-time evaluation. To ensure substantial evaluation of the conditions listed in table 15, each system should remain installed for at least 6 months.

Task 5: <u>WADS algorithm enhancement</u>. The objective of this task is the optimization of the WADS system performance utilizing evaluation results. The installed WADS systems would be upgraded to reflect the most recent optimization changes to the algorithms.

Task 6: <u>WADS Range Extension</u>. The WADS algorithm's range of operation need to be extended from 500 ft (152 m) to 1000 ft (305 m) to meet the suggested specifications listed in table 12. Techniques related to signature analysis and edge recognition should be considered to accomplish the range extension.

Task 7: <u>Traffic parameter derivation/database generation</u>. This task involves the derivation of various traffic parameters not accomplished under the current WADS contract. This can be obtained by the presence/passage signals generated by WADS or in some cases can be measured directly. Traffic measures that cannot easily be obtained by conventional equipment include queue lengths, speed profiles, stops, energy consumption, and density, are of vital importance if wide-area detection is to be fully utilized in advanced applications such as incident detection or intersection control.

Table 15. Real-time evaluation conditions.

Conditions	Description
Ranges	nearest to camera, 200 ft (61 m), and 500 ft (152 m).
Times of Day	day, night, dawn/dusk.
Artifacts	vehicle shadows, wind, vehicle occlusion, reflections, cloud/fixed shadows, wet roads, icing roads.
Traffic	normal, congested, stopped.
Vehicles	cars, semis/busses, motorcycles
Atmospheric Transmission	clear, hazy, rain, fog, sleet, snow.

Incident Detection

The primary objective of this application is the adaptation of existing incident detection techniques, enhanced with the decision-making capabilities of modern artificial intelligence methods, to fully utilize the wide-area sensing capabilities of WADS for generating a fully operational Enhanced Incident Detection System having reliable freeway incident detection capabilities. This system has the potential to provide superior performance to those of existing incident detection algorithms.

Incident detection algorithms are currently a useful supplement to other manual techniques (such as motorist call systems, citizen's band radio, cellular telephone, police and service patrols, and manual CCTV surveillance) for the identification of an incident. The capability to rapidly detect freeway incidents is an essential element of effective freeway management, and for this reason, a significant amount of research has been spent on the development of automated freeway incident detection techniques.

Although the majority of operational systems use the incident detection algorithms developed during the 1970's, limited research in this area continues. (See references 30 through 35.) A procedure was developed for the automatic detection of capacity-reducing incidents using time-series analysis techniques.[36] Additional work performed was subsequently reported in Traffic Engineering and Control.[37]

Research related to the development of new incident detection algorithms is continuing. However, the emphasis is shifting from the exclusive use of loop detector outputs analyzed with heuristic decision logic, to the use of expert systems software that combines inputs from loop detectors, with observer data in an attempt to enhance the incident detector process. Work in this area is currently underway on the 401 motorway in Toronto, Canada with additional effort scheduled to begin on the Santa Monica freeway near Los Angeles, California.[38]

It is interesting to note, that with the exception of reference 36, and the expert systems software developments in California, little additional incident detection work has been reported in the literature. The absence of ongoing work in this area does not reflect a reduced need for automated incident detection algorithms, but rather the general feeling on the part of research agencies that the existing results cannot be significantly improved as long as surveillance is based on the use of the loop detector.

Implementation of WADS for incident detection can be made in two phases. In the first phase, laboratory software for an enhanced incident detection system can be developed. The second phase would involve the field installation and evaluation of that software. Included in Phase II is the installation of WADS detection systems to provide traffic flow information to the incident detection system.

The following list of 6 tasks could be utilized to guide the development of the enhanced incident detection system.

Task 1: WADS system enhancement. Further functionality required by incident detection that has not already been previously implemented would be added to WADS. Possible enhancements would include the ability to reposition the detectors under software control. This capability can be used to search for the end of a queue as well as monitor the shoulder of a road for stopped vehicles.

Task 2: Incident Detection Algorithm Development Facility. The objective of this task is the development of a facility to support the incident detection algorithm development. Not only will the development time of the incident detection algorithms be reduced, but the same system can then be used as the field installable version of the enhanced incident detection system with minimal changes. Development of all necessary user interfaces for the final system should also be accomplished in this task.

Task 3: Incident Data Collection. The collection of incident data is necessary for the development and testing of the incident detection algorithms.

Task 4: Incident Detection Algorithm Software. The algorithms should rely exclusively on inputs from the WADS equipment. Work performed during this task should build on existing incident detection strategies while taking advantage of the enhanced information provided by WADS and of recent developments in the field of artificial intelligence i.e. expert systems. A design performance objective for this application should be an incident detection probability of 95 percent with a false detections below 1 percent.

Task 5: Incident Detection System Laboratory Testing. This includes the final set of system laboratory tests to be performed prior to packaging and shipment to a field installation. Incident data collected during Task 3 would be used as the basis for these tests.

Task 6: Field Implementation. In this task, Phase II will be initiated. This includes several subtasks such as Incident detection site selection, WADS and Incident detection system field installation, algorithm optimization, evaluation and acceptance testing, and documentation.

Critical and Coordinated Intersection Control

The primary objective of this application is to employ the WADS detection technology for critical intersection control, i.e. an application that requires extensive detectorization. This critical intersection control should also be extended to intersections requiring coordination with adjacent intersections.

A recently developed control strategy for the FHWA called the OPAC algorithm for critical intersections requires extensive loop detector placement.[39] Although the OPAC strategy has been shown to be quite effective in recent implementations, the estimated conventional-loop cost is $25,000 to $30,000 per intersection. WADS technology can certainly be accomplished below this cost while maintaining the flexibility of changing the detector configuration and the number of detection points and extracting additional data enhancing the efficiency of the control strategy. Therefore application of WADS for implementing OPAC is appropriate.

Implementation of WADS for critical intersection control can be made in two phases. In the first phase an integrated advanced control system (ACS) can be developed based on the use of the OPAC and WADS technology. This system can provide signal control at a single intersection for which coordination with adjacent intersections is not required. The approach proposed for Phase II enhances the ACS system to provide signal control at intersections requiring coordination with adjacent intersections. While the same intersection hardware design will be used, the software will be modified to permit distributed intersection control without receiving timing commands from a central location.

Specifically, the following tasks are proposed for implementing the WADS system for CIC.

Task 1: <u>Select Test Site</u>. Select a critical intersection suitable for OPAC implementation.

Task 2: <u>Determine Camera Placement</u>. Select camera placements satisfying the OPAC requirements; the objective is to minimize the number of cameras and other equipment at the intersection. Experimentation with wide angle lenses should be performed in this task.

Task 3: <u>Emulate Camera Placement/Test and Calibrate WADS</u>. Make videotapes at the selected camera locations for testing and calibrating the WADS system and for fine tuning the selected camera placement. Verify WADS accuracy for OPAC utilized traffic parameters.

Task 4: OPAC Software Modifications. Some software modifications must be made to the OPAC algorithm for operation in a stand-alone configuration that is interfaced with the WADS system. While no major changes need to be made to the basic OPAC strategy, modifications should take advantage of the enhanced detection capabilities of the WADS system. These modifications could include use of the directly measured WADS parameters such as queue lengths, discharge rates, and travel times.

Task 5: Interface WADS and OPAC. The objective of this task is to interface the OPAC controller with the WADS detection system. This should initially be performed in the lab and the system can be tested using the tapes made in Task 2.

Task 6: Field Installation/Implementation. The integrated system produced in Task 5 would be installed at the selected intersections and tested for error free operation. Then the system should be allowed to run autonomously and be adjusted accordingly.

Task 7: Evaluation and Acceptance Testing. Once the system is operating error free, manual evaluation as to the effectiveness of the OPAC algorithms utilizing WADS detection can be performed. It may be necessary to suggest/implement improvements to the system after the evaluations are complete.

Task 8: Extend ACS to Coordinated Intersections. In this task, Phase II will be initiated. This includes several subtasks such as OPAC algorithm modifications, system simulation and refinement, system integration and testing, field installation, evaluation and acceptance testing, and documentation.

10 CONCLUSIONS

From the results presented in section 8 it should be evident that the WADS technology was advanced significantly over the course of this contract. Synergy between real-time development on other contracts and this contract's focus on artifact handling resulted in a robust real-time vehicle detection system which could be extensively evaluated. Much work remains in order to completely characterize performance in the presence of all possible artifacts, but by all indications, the elusive goal of the WADS research and development is extremely close to fulfillment: the cost-effective ability to detect vehicles via video cameras with accuracy sufficient for application in automated traffic control and surveillance. This was clearly demonstrated in live benchmarks of the WADS system described here in several cities in the U.S. and abroad. In these benchmarks the system was connected to several live cameras in each location and the detection results were visually verified. According to observers at two European demonstrations and an Australian presentation, the U.S. based WADS system is not only the most sophisticated, but also the most advanced one available today since it indeed operates in real-time, detects traffic at multiple spots, and has the accuracy required for real applications. Summarizing, the main achievements of this project are:

* An extensive database of video traffic data, populated with imagery especially chosen to be troublesome, has been collected and cataloged for this effort, and a 30-minute video disc with representative video sequences has been made. This video disc, in conjunction with an earlier one, can serve to test all future developments of video-based traffic detection systems.

* Algorithms have been designed and implemented to detect vehicle presence, passage, and speed that perform adequately under all conditions: daytime, nighttime, dusk, and dawn; shadows, headlight reflections, and glint; rain and snow; and changing road-surface conditions caused by cloud shadows, camera AGC flux, and congestion.

* These algorithms have been validated on over 32 hours of artifact-laden video from optical video disc, videotape, and live traffic surveillance cameras installed in the field. Performance is within range of requirements of traffic control applications.

As mentioned in section 3, despite major worldwide efforts to develop a machine vision system for traffic surveillance and control, a real-time device having the capabilities and performance required for practical applications has been elusive. The live demonstrations of the system in its present form, to professional engineers and potential users, has generated favorable comments. When this evidence is combined with the results of detailed evaluation presented here, it is not hard to explain the enthusiasm of the practicing engineers who keep asking for applications of the WADS technology in various presentations and professional meetings.

The serious consideration of WADS by several State transportation agencies at this stage of the development is primarily owed to the system's expected impact in traffic surveillance and control. Indeed, the major advantages of this machine vision system lie in the multispot, multilane wireless detection capabilities which, along with recent advances in image understanding, should essentially transform it to an "electronic eye" for computerized surveillance and control or for automating time-consuming and expensive functions (performance evaluation, derivation of measures of effectiveness, etc.).

11 RECOMMENDATIONS

Despite the successful completion of this project, a rigorous and deliberate followup development plan must be initiated to ensure transfer of the technology to the end users (cities, municipalities, etc.). Products and applications must be developed that can be quickly implemented in the field for the benefit of the motoring public. As mentioned in section 9, the WADS system developed in this project is not a production line prototype and needs to be extensively tested in the field to gain the confidence and trust of practicing engineers. To be sure, the enthusiasm and support gained to this point will evaporate if introduction of the technology in the field is not quickly followed through with further development and demonstrations. Interruption of the R and D effort can be damaging and costly as it will adversely affect the momentum gained so far.

Although product development should be performed by the private sector, the present state of the WADS system is not sufficiently advanced to entice private capital. For this reason a field application involving extensive testing, calibration, and automated comparison with loop detectors, colocated with WADS, over a 9-month period of continuous operation is currently underway. Two WADS system will be installed on I-35W in Minneapolis through a MnDOT/FHWA demonstration project. In this project, initiated in June 1989, software for incident detection will be developed and implemented using 20-25 WADS systems on Interstate I-394 by 1991. This is the first and largest known demonstration project involving a WADS application worldwide.

Another subject that requires immediate attention is derivation of traffic parameters from the presence and passage signals generated by the WADS system. This issue was not seriously addressed in the current contract due to the lack of sufficient funding. It should be evident, however, that once the detection signals are successfully generated by WADS, traffic parameters can be extracted.

Following the testing and validation phase, extension of the system's range of operation through signature analysis and edge recognition should be performed. This will allow direct separation of vehicles during congested periods at longer ranges and measurement of queue lengths and densities (currently this can be derived indirectly). Unlike the testing and calibration, this will require more substantial effort and will lead to the second generation of the WADS system described herein.

In parallel to the previously mentioned system improvements, development of the applications described in section 8 should be initiated. The most direct application is employment of WADS for generation of databases suitable for real-time traffic control and vehicle guidance/navigation. The advantage lies in the quick and efficient installation of the system in heavily congested areas where loop installation becomes expensive, problematic and requires substantial installation lead time while disrupting traffic operations. Another high-priority area is critical intersection control. This application is timely in view of the recent FHWA development of the OPAC critical intersection control algorithm which requires substantial instrumentation and detection flexibility.

Prior to implementation of the WADS technology a word of caution is appropriate. The device should not be viewed as a simple replacement for loops, which will continue to serve their intended purpose for some time. Instead, WADS should really be viewed as a wide area detection system, i.e. it can collect area data as well as point-only data. As such, it leads to new potential applications that have not been seriously attempted before. Therefore, initial applications of the technology should be selected with caution to capitalize on the WADS capabilities.

Because of the promise of WADS technology, there has been substantial interest by States, cities, and municipalities in implementing it. One way of financing WADS related applications is through demonstration projects. At least one State is pursuing this avenue while several others are considering similar approaches. However it becomes increasingly apparent that Federal involvement and support in such projects is essential.

Finally, given the momentum of the European and Japanese research initiatives in advanced traffic control technologies, there are few areas in which the U.S. is currently still leading. This project ensures that machine vision is one of these few.

Appendix A

SHADOW DETECTION BY MEDIAN FILTERING

The Problem

Shadows and glare on the road from vehicles in adjacent lanes cause false detection. Distinguishing shadows or other flat artifacts from cubics is a general, difficult, problem in image processing. In other applications it has been proposed to solve this by means of stereopsis; perspective can also be used for 3D object reconstruction.[40,41] Neither of these methods can be applied in our case. A variation of the first was proposed in a previous study, but it was decided that the increase in cost it represented makes it impractical.[7] The second method can only be applied to a sequence of images in two dimensions and, consequently, it is not usable in our case.

The problem, then, consists in identifying shadows of glare in order to avoid false vehicle detection. This must be done without using additional hardware (i.e. using only the basic system with one camera and line detection of vehicles). In addition, the algorithm used for this purpose must be fast enough for real-time applications.

A Novel Approach

Instead of trying to determine signatures of cubics and "flat objects" on the road in order to identify them, the idea is to recognize a marking of known width located in the region of vehicle detection. Any other mark of different width should be rejected. In addition, if the mark is covered by a shadow or glare, it should still be detected. When the mark is covered by a vehicle, it is no longer visible and, consequently, it will not be detected. If vehicle detection and mark detection signals occur simultaneously, this would indicate a false vehicle detection due to a shadow or glare, because it is impossible to detect a real vehicle and a mark simultaneously. This concept is illustrated in figure A.1.

Median Filtering

The simplest way of detecting a mark of known width and grey level, placed on a background with a very different gray level, would be by thresholding the image and thus generating a binary image in which the line is represented by zeroes and the rest of the image by ones (or vice-versa). With the highly variable levels of illumination existing in traffic applications, complicated by the intended goal of detecting a mark in the presence, and absence, of shadows or glare, this method is totally unreliable, even if dynamic thresholding would be used. A more robust mark detection algorithm has to be used.

Median filtering is a nonlinear filtering technique that can be used instead of averaging when a low-pass filter is needed.[42] It is generally implemented as a window operator. The values of all the pixels inside the window are ranked and the median value is chosen as the output of the filter. Median filters have several properties which makes them useful in this and similar applications, such as detecting guidance lines for mobile robots.[43] Perhaps the most useful property of a median filter is its ability to remove "impulse noise" without changing the shape or location of edges.[44] The width of the impulse that can be removed by a median filter depends

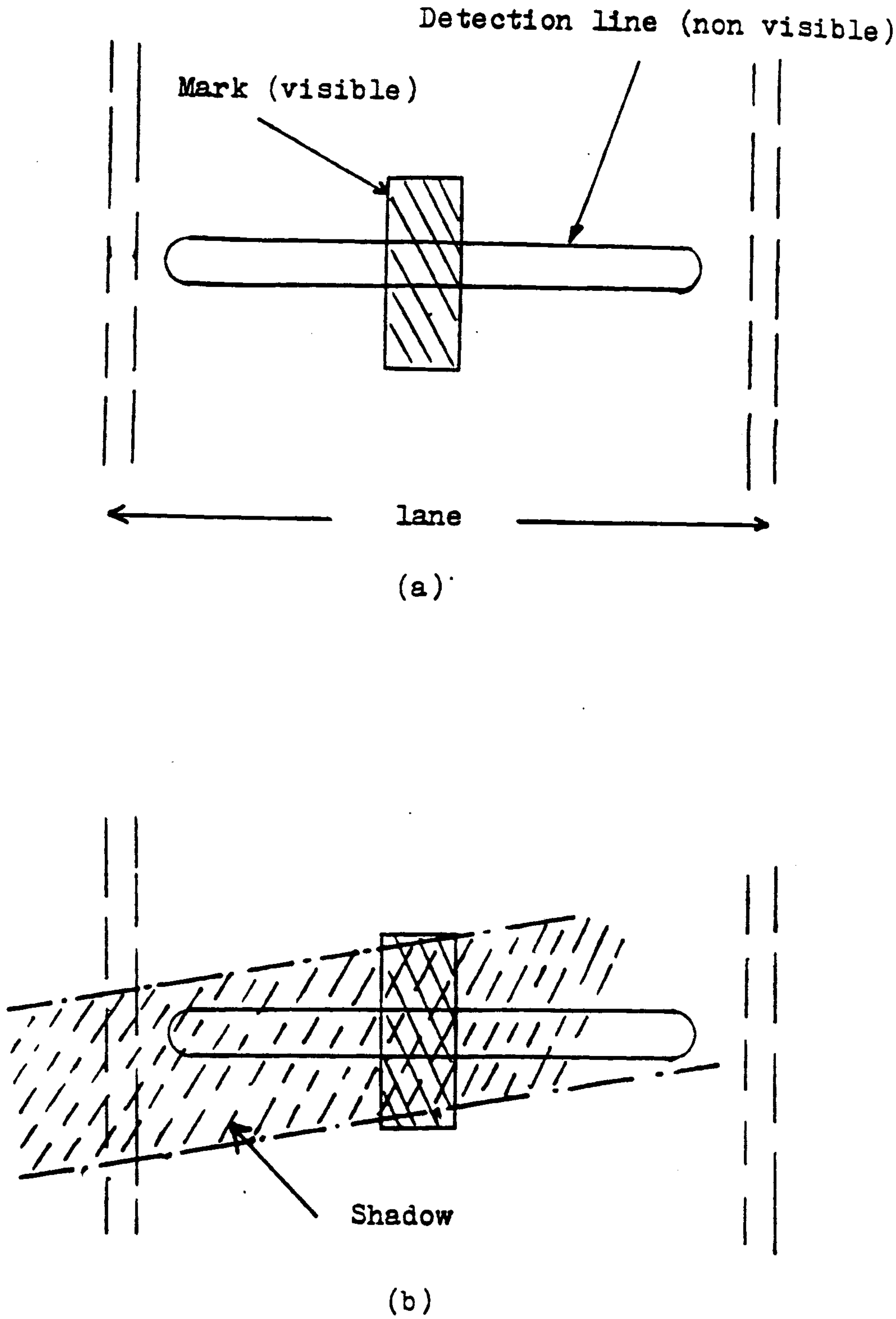


Figure 17. A "Detection mark" to separate shadow detection from vehicle detection.

on the order of the filter. A median filter ϕ_K has order k and a window width:

$$K = 2k + 1 \tag{13}$$

in pixels. The pixel under consideration is always at the center of the window and it is its value which is replaced by the median gray level value inside the window. The median filter is applied to a complete detection line. For the first k and the last k pixels, values equal to the first and the last pixel gray level value are replaced, as needed, to complete the missing pixels in the window. Pulses with a width less or equal to k are not passed, while pulses with a width larger than k are passed.

Several efficient methods have been devised for applying median filters to an image. The fastest for our application makes use of the overlap from one window position to the next. In our one-dimensional case, a pixel only changes value when the window is shifted over to the next pixel. The method is called the histogram method. A histogram is taken of the window in the first positions, and the median is derived. For subsequent window positions, the pixels which move out of the window are removed from the histogram and the new pixels are added. The median is then updated to represent the distribution in the new window position. The method has been shown to be considerably faster than conventional sorting algorithms. The algorithm consists of the following steps:[44]

1. Set up the gray level histogram of the first window and find the median. Also, make the count m of the number of pixels with gray level less than the median.

2. Move to the next window by deleting the leftmost pixel of the previous window and adding one pixel to the right. The histogram is updated and so is the count m. Now m stores the number of pixels in the current window having gray level less than the median in the previous window.

3. Starting from the median of the previous window, move up/down the histogram bins one at a time if the count m is (not greater)/greater than the number of pixels in a window divided by two. Update the count m until the median bin is reached.

4. Stop if the end of the line is reached. Otherwise, go to step 2.

   Note: In step 3, if the count m is (not greater) than (number of pixels in a window divided by 2), then we may have the same median as before and, therefore, do not need to move.

By using two median filters of different orders, it is thus possible to implement a filter to detect marks within a given width range. The first test image is a digitized (256 X 256 pixels) gray level (256 levels) image showing a laboratory floor with a black stripe on it. The floor is highly textured with a "salt and pepper" pattern. The gray level image of a row at the center of the image is shown in figure 18. Notice the wide variation of gray level corresponding to floor texture and the low level, with a width of 11 pixels, corresponding to the black stripe. Two median filters process this line, one with k=9 and the other with k=12. Their outputs are shown in figures 19 and 20, respectively. The absolute value of the difference of these two filters eliminates the part of the response common to both, thus leaving only the response common to both, thus leaving only

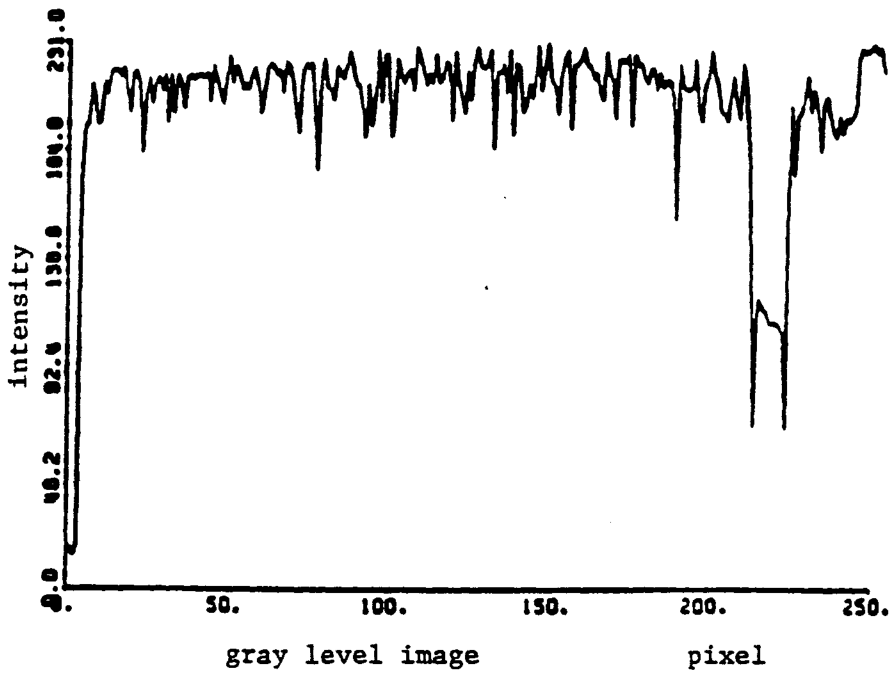


Figure 18. Gray level output of one line at the center of the image.

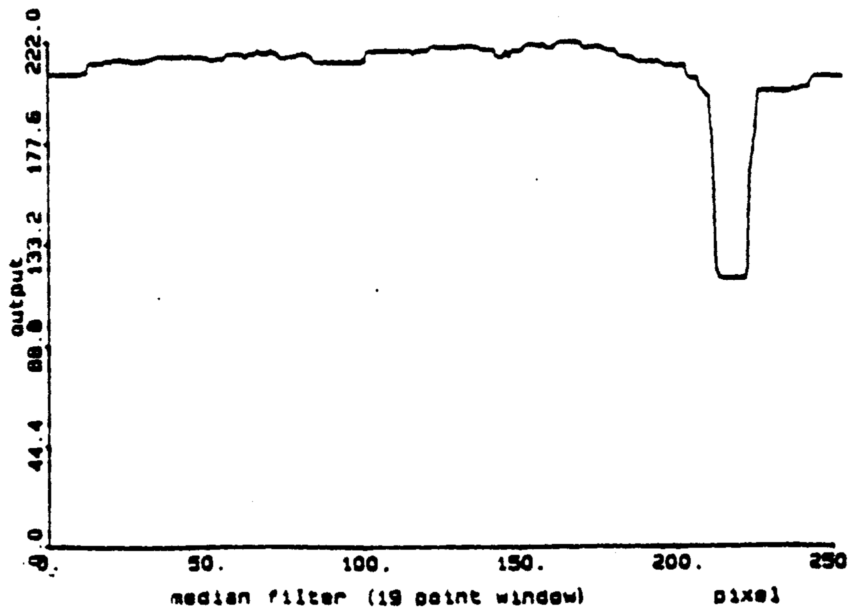


Figure 19. Output of median filter of order k=9 for the image of figure 18.

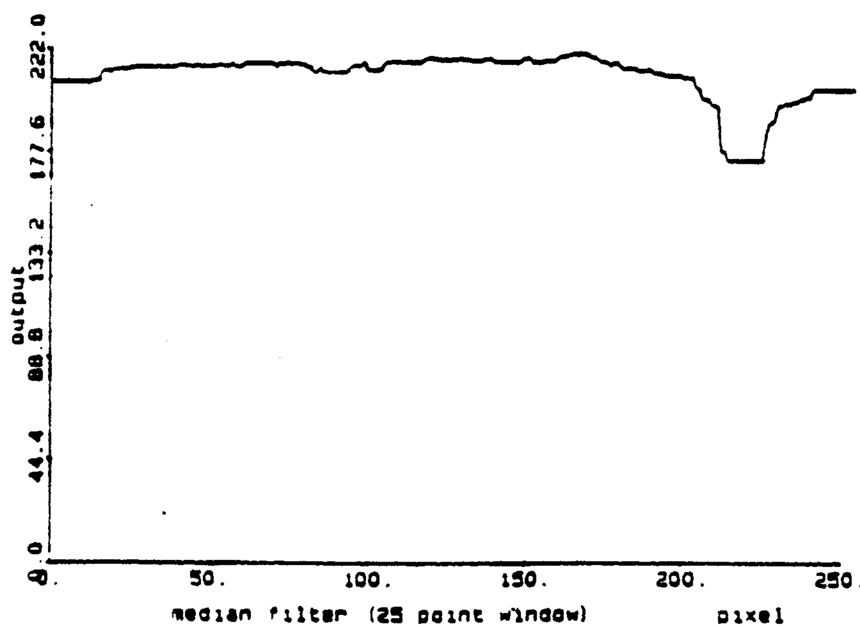


Figure 20. Output of median filter of order k=12 for the image of figure 18.

the response due to the 11 pixel wide stripe. Only "pulses" with a width of 10 and 11 pixels are passed by:

$$DOM_{k,j}(i) = \phi_k(i) - \phi_j(i) \tag{14}$$

The more accurately the width of the mark is known, the closer the order of the two filters can be made. The output of the DOM (Difference Of Medians) filter is shown in figure 21. Notice that in figure 21 the vertical scale is not the same as in figures 19 and 20.

Experimental Results

Two additional scenes were used for testing. In the first one, a white stripe was laid on a dark, relatively homogeneous, background. The stripe was 22 pixels wide. The two median filters were of order 23 and 21, respectively. The gray level image of row 100 (slightly above the center of the image) is shown in figure 22 and the result of the DOM in figure 23. Good detection is obtained. Next, a shadow was cast on the stripe. The gray level image was obtained for two rows, one in the area without a shadow area, row 105, figures 24 and 25, respectively. The order of the two median filters was the same as before (23 and 21). The DOM filter output is given for both cases in figures 26 and 27, respectively. In both cases detection is excellent. Notice that the region of very low intensity due to the object casting the shadow is eliminated by the DOM filter.

The second scene, was a black stripe laid on a highly textured floor. In this case the stripe was 14 pixels wide and the two median filters were of order 12 and 16, respectively. The gray level image of row 120 is shown in figure 28 and the output of the DOM in figure 29. The result

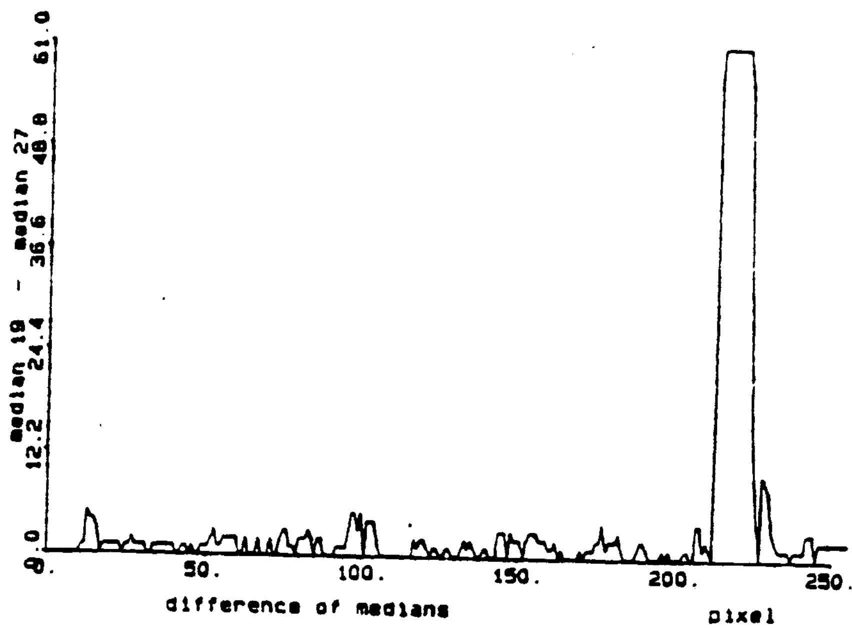


Figure 21. Difference of medians, absolute value, for filter output of figures 19 and 20.

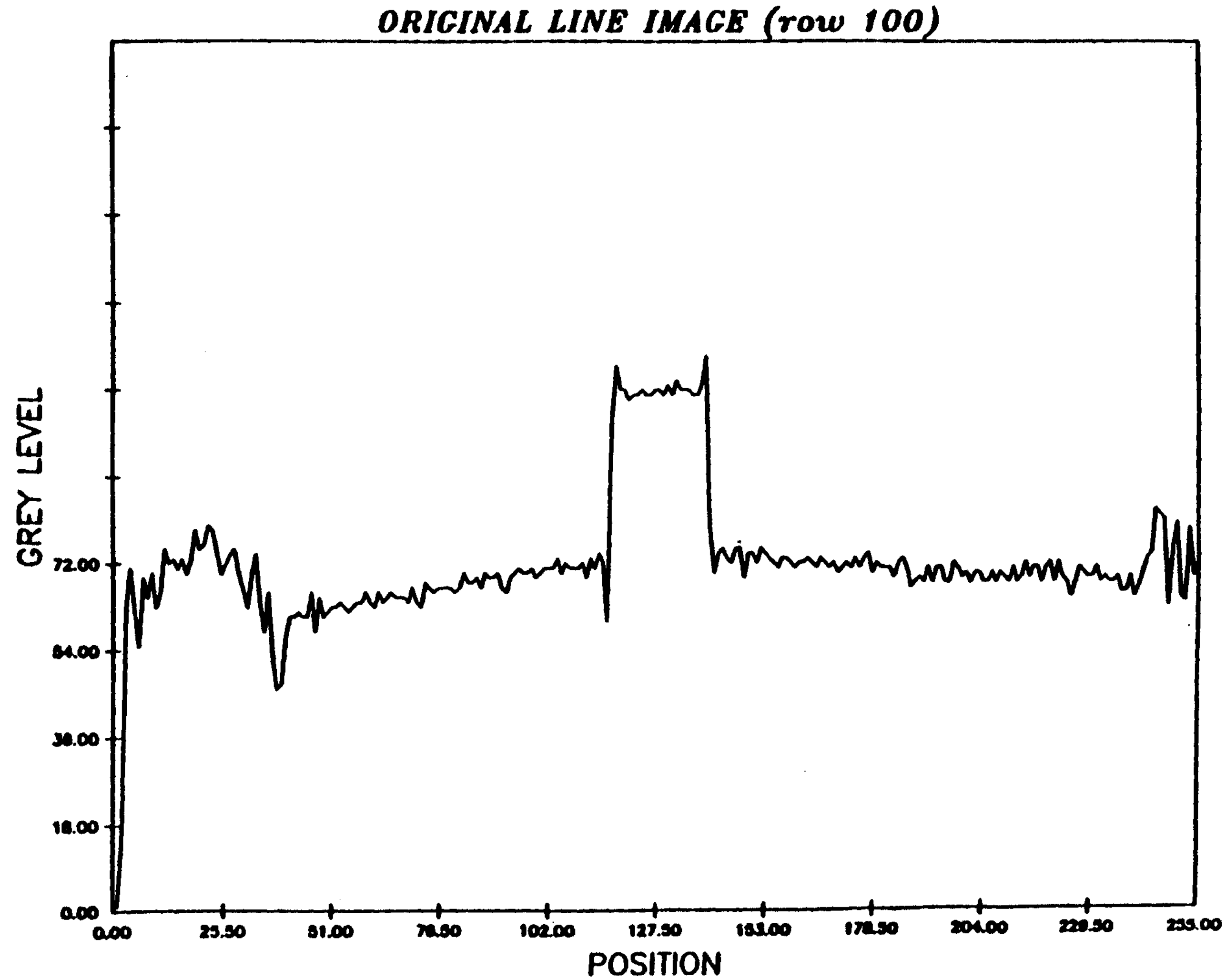


Figure 22. Gray level image of row 100 for first scene.

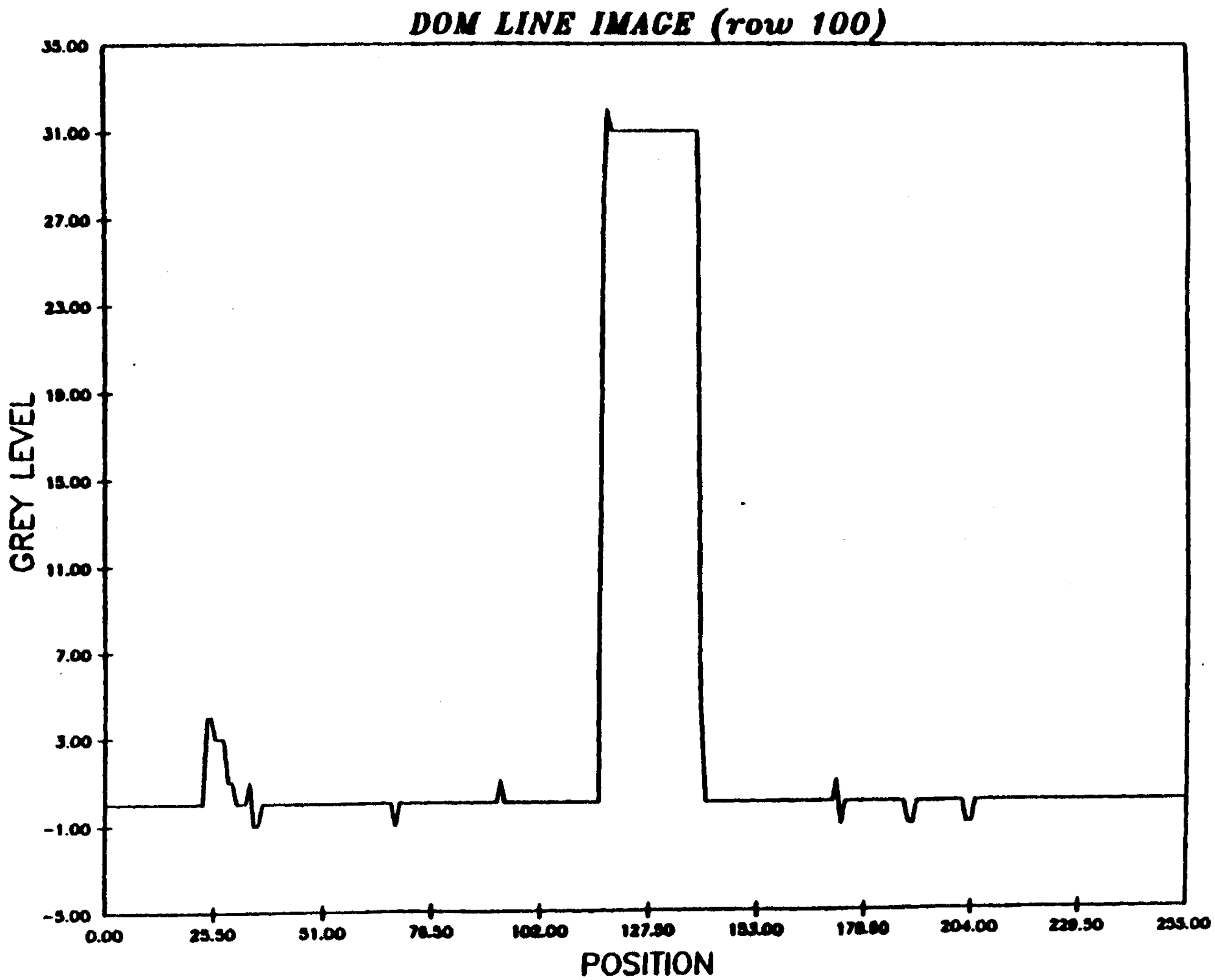


Figure 23. Difference of medians for gray level image in figure 22.

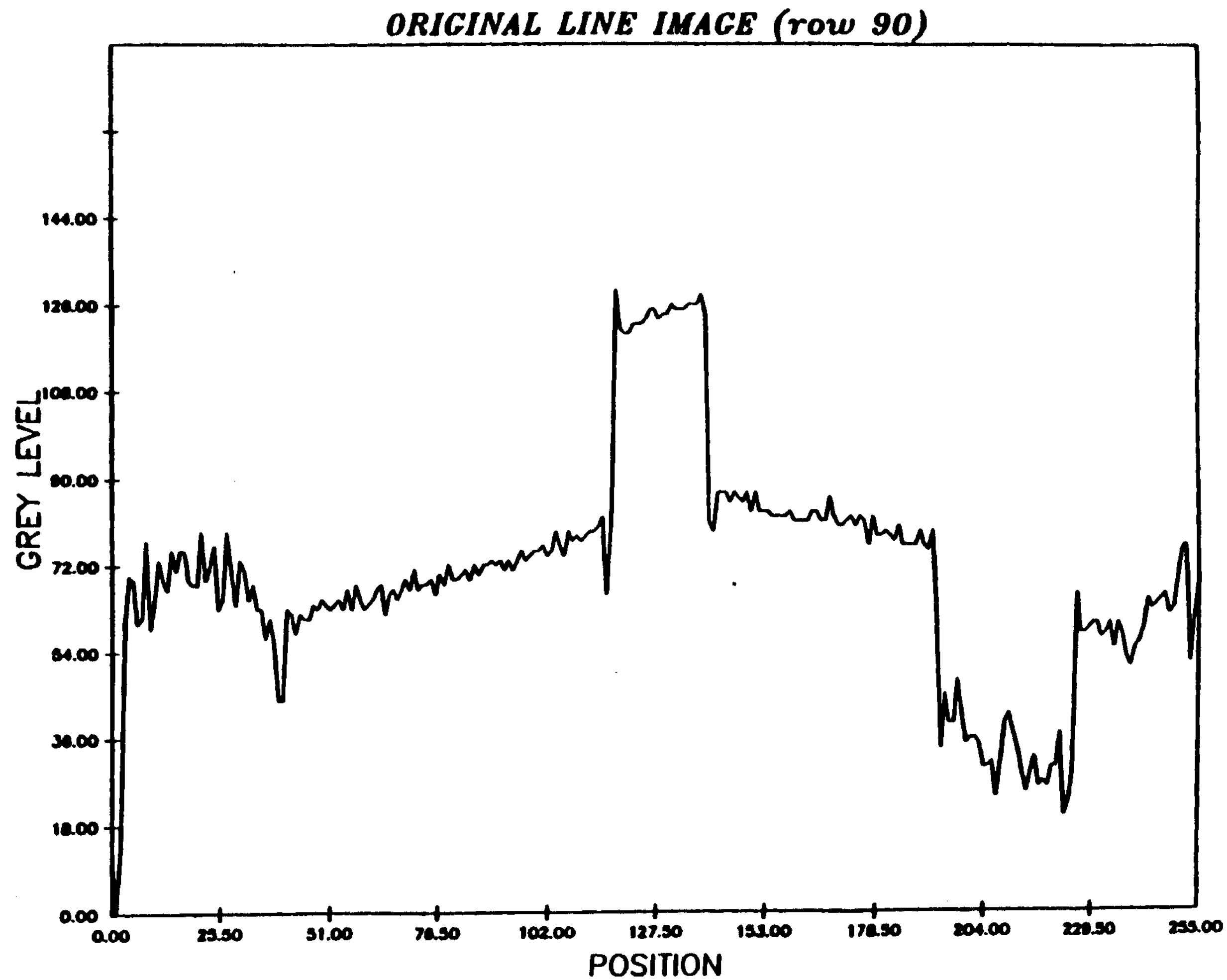


Figure 24. Gray level image, row 90, for first scene (no shadow).

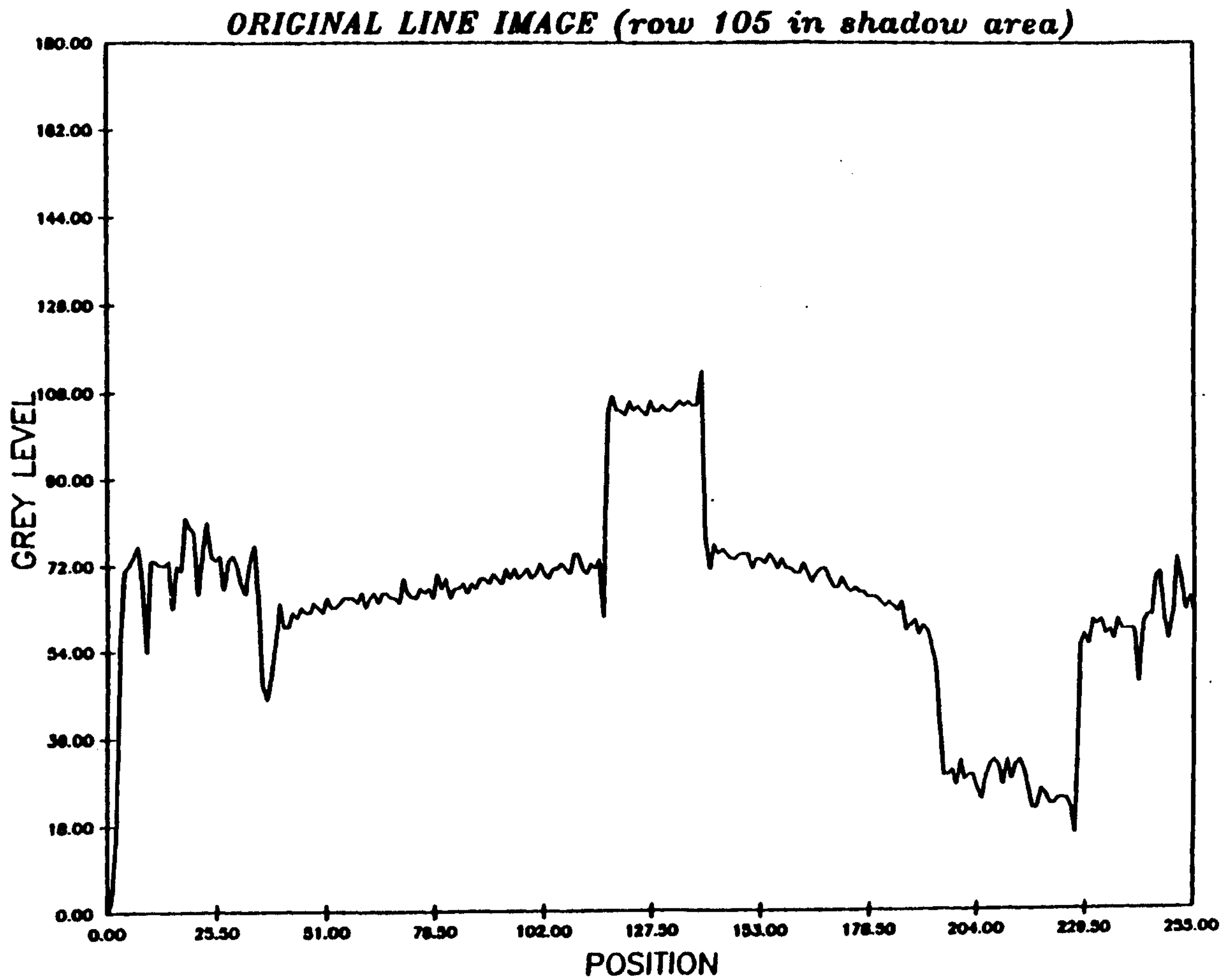


Figure 25. Gray level image, row 105, for first scene (with shadow).

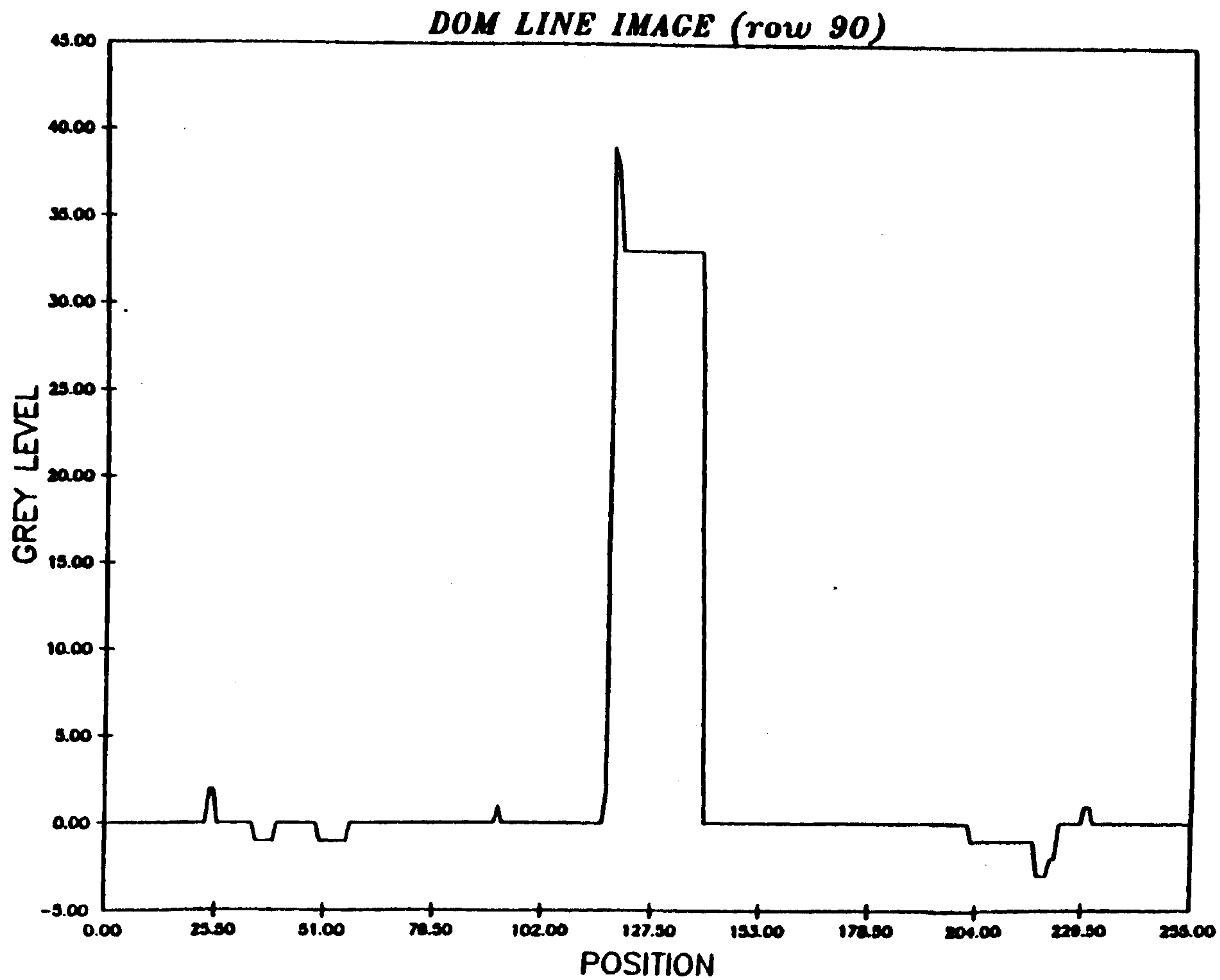


Figure 26. Difference of medians for gray level image of figure 24.

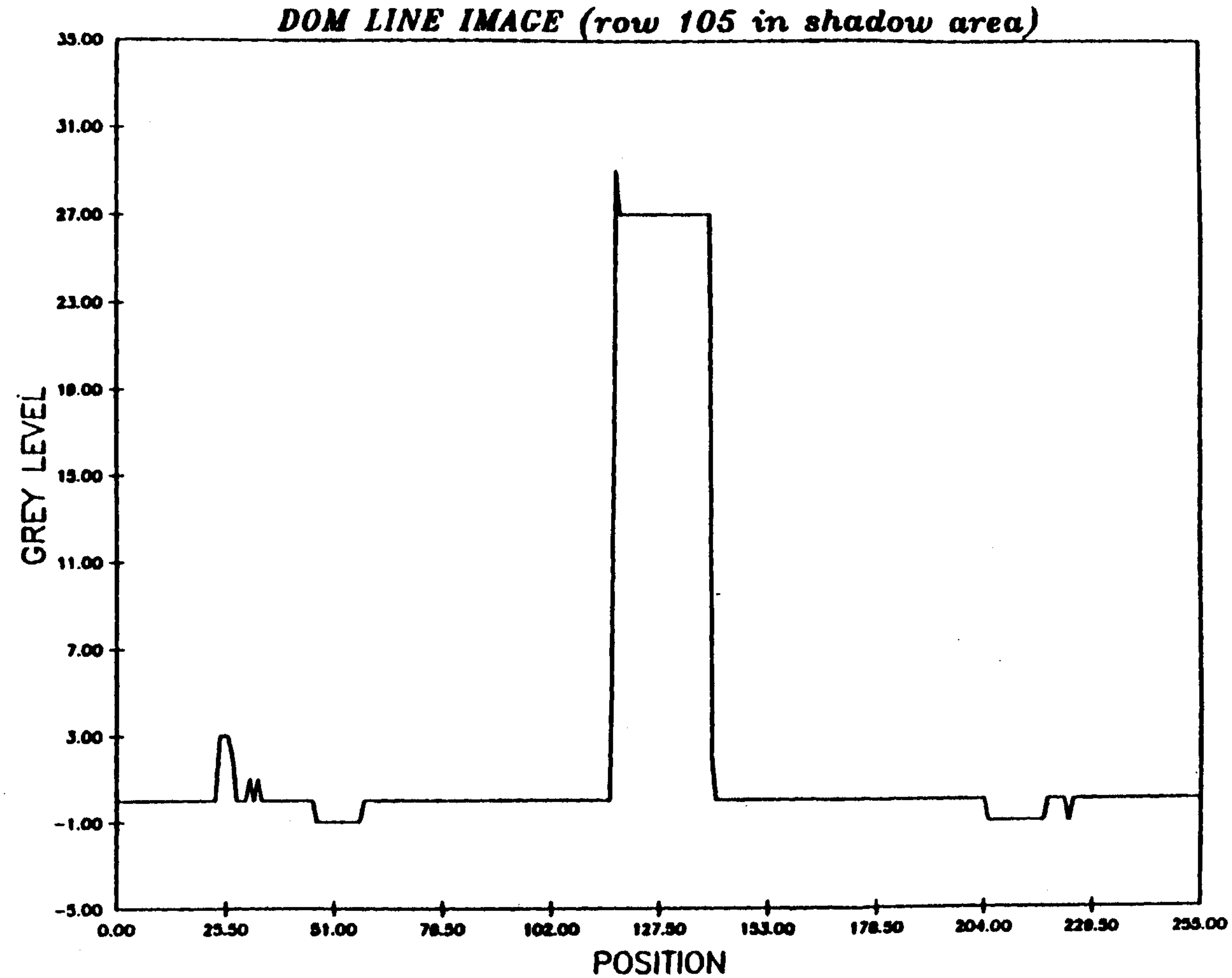


Figure 27. Difference of medians for gray level image of figure 25.

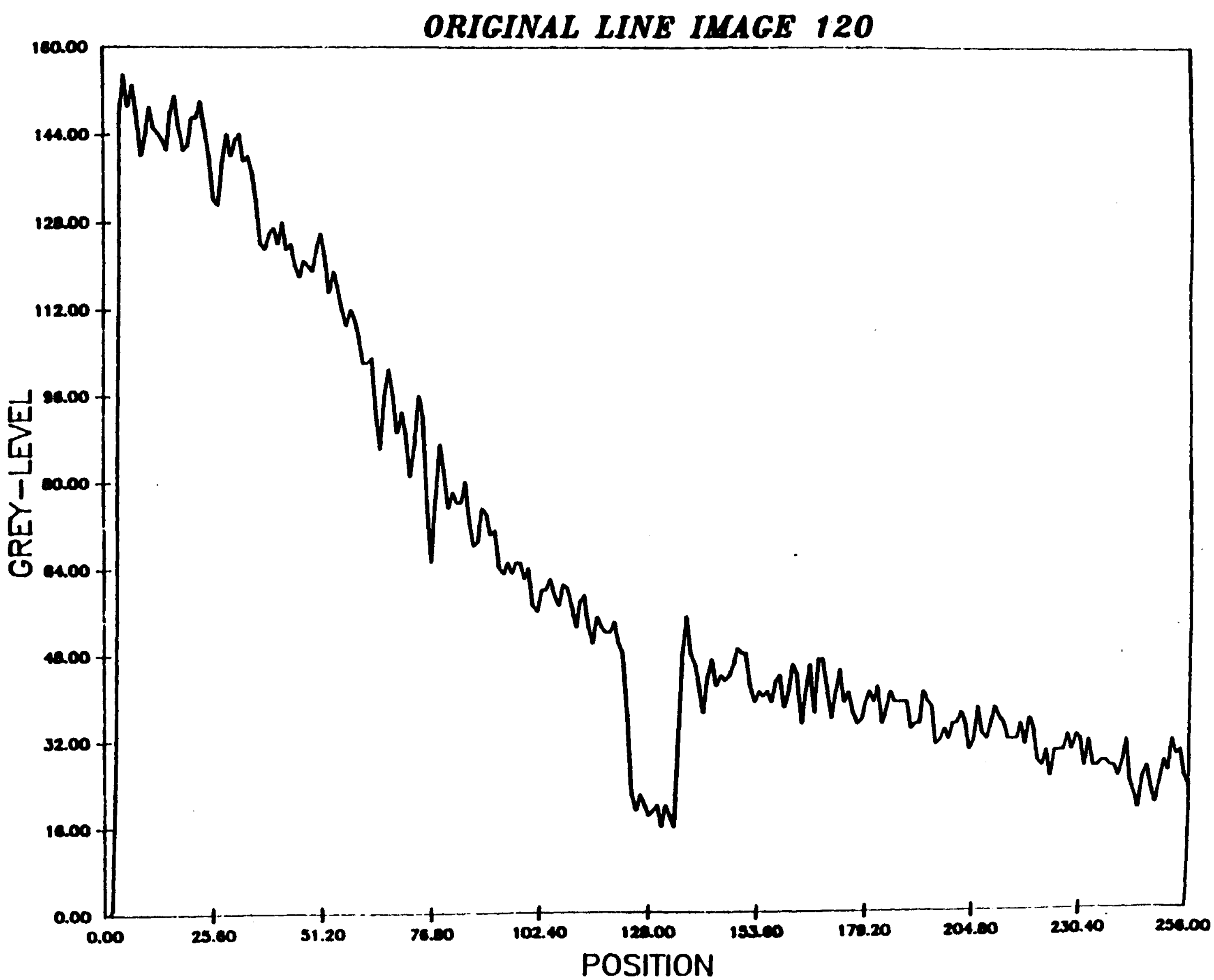


Figure 28. Gray level image, row 90, for second scene.

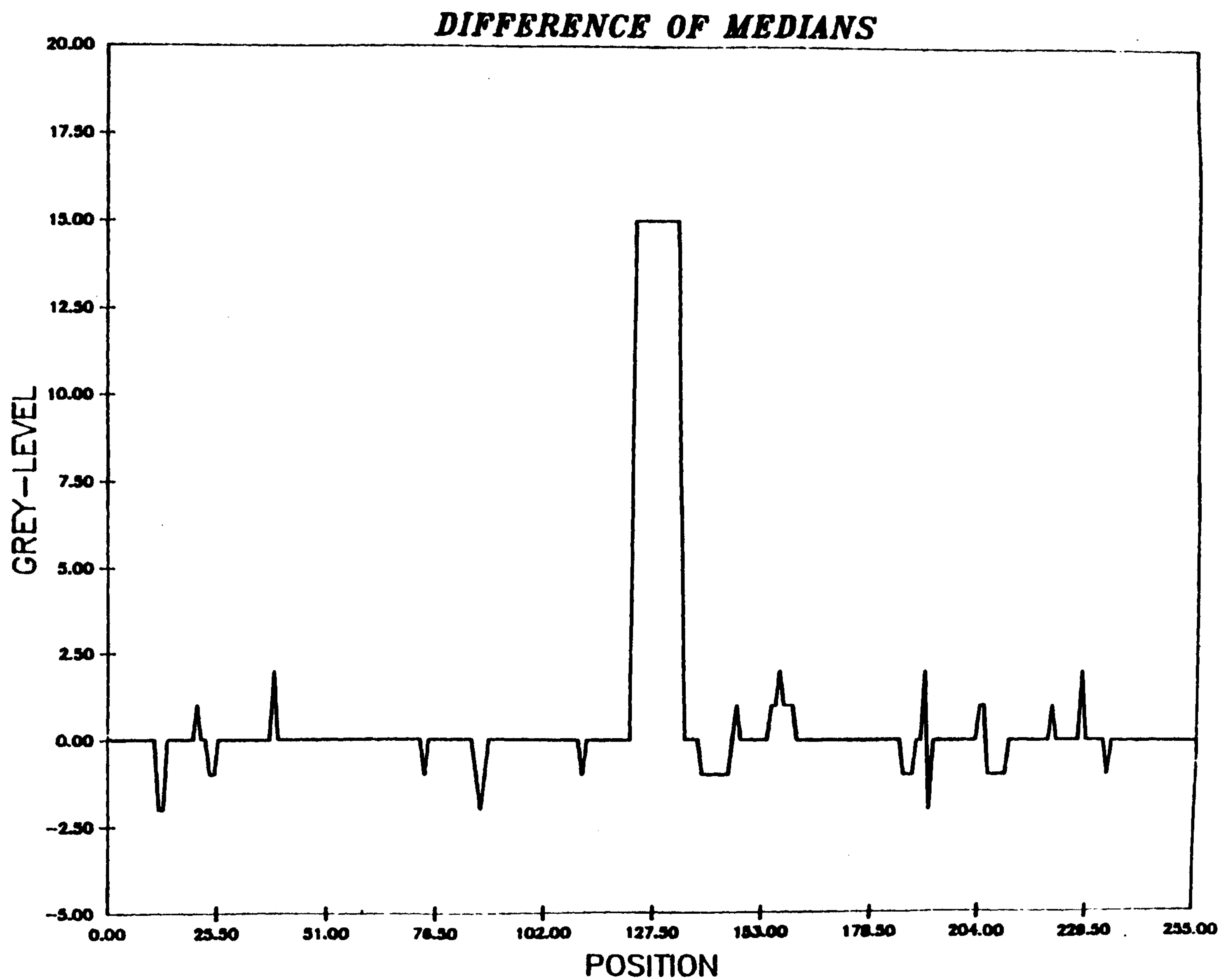


Figure 29. Difference of medians for gray level image of figure 28.

is satisfactory. This situation is not likely to occur in practice, because in most cases (maybe all cases), the stripe will be white on darker background, a case simpler than the one shown here.

Use of Median Filters without Detection Marks

In many cases, specially when it is desired to change the detection line position in the image, it is not practical to set detection marks on the highway, especially during periods of reconstruction. In addition, local and state regulations may forbid the use of highway markings not specifically required by traffic (such as "straight" or "turn" arrows).

It is, then, convenient to develop an alternate method to allow for separation of 3D objects (i.e. vehicles) from shadows or glare produced by vehicles on adjacent lanes.

If we assume that: a) moving vehicles will not obstruct lane boundary lines and b) shadows or glare start at lane boundary line at the detection line, it is possible to use median filtering techniques to separate vehicles form shadow/glare disturbances.

Figure 30(a) shows a vehicle traveling close to, but separated from, the lane edge. This case will be correctly identified as a vehicles by the method described previously. Figure 30(b) shows a shadow produced by a car in the left lane (from the reader's point of view) and traveling from top to bottom. The shadow, at the detection line, starts at the edge of the lane and will be correctly identified as a "non-vehicle detected". Figure 30(c) is similar to figure 30(b), but the shadow has moved down and the detection line now has "non-shadow" pixels at both edges of the lane. This situation, however, will not produce a false vehicle detection if sufficient delay exists between detections by one of the two

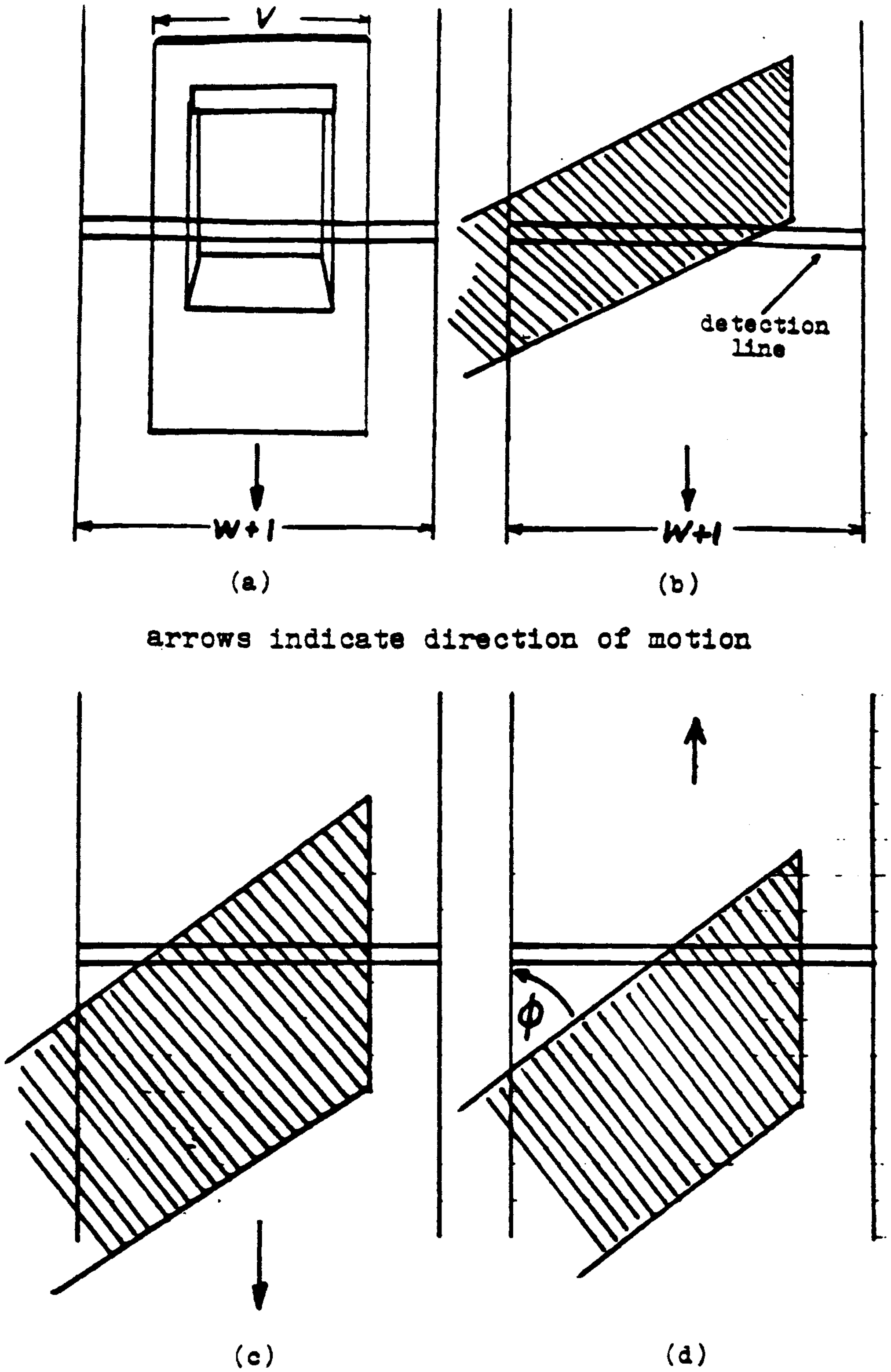


Figure 30. A vehicle and shadows on the detection line.

median filters to allow the complete shadow to disappear before the next detection occurs. The opposite situation is shown in figure 30(d). The shadow is now produced by a vehicle traveling on the left lane, but from bottom to top. When the shadow comes from the left at an angle $\phi<90$ degrees, as shown in the figure, the first portion of the shadow to be detected is isolated from the edges and a false detection can occur. This could be prevented by a more sophisticated algorithm which would monitor detection by one of the two median filters until detection is cleared. If before being cleared the detected "object" covers the lane boundary line, it would be a shadow. Otherwise, it would be a vehicle. This procedure, however, would require much faster sampling of the detection line and might represent a too heavy processing burden. This problem will not exist if the shadow covers the complete lane, as shown in figure 31(a). For angles $\phi>90$ degrees, the situation for shadows from both sides is summarized in figure 32.

Essentially, the algorithm is the same as that explained previously. The difference consists in the choice of window width and, in consequence, in the number of pixels appended at both ends of the detection line. For a lane of width W+1 pixels and a filter of order k, i.e. window width K = 2k + 1, k pixels with intensity equal to that of lane pixel 0 must be appended to the left of the detection line and k pixels with intensity equal to that of pixel W must be appended to the right of the detection line.

$$V_1 \leq V \leq V_2 \tag{15}$$

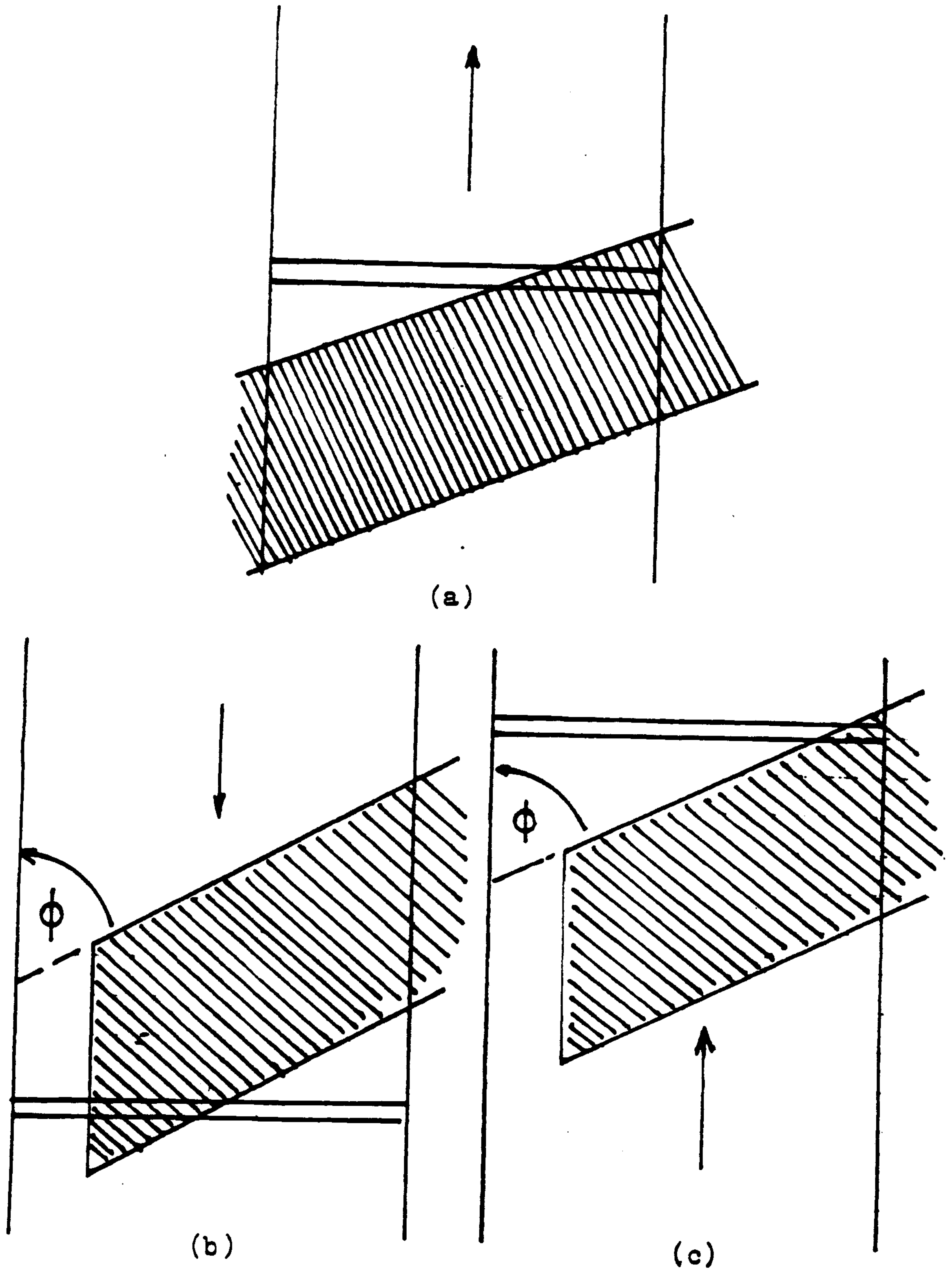
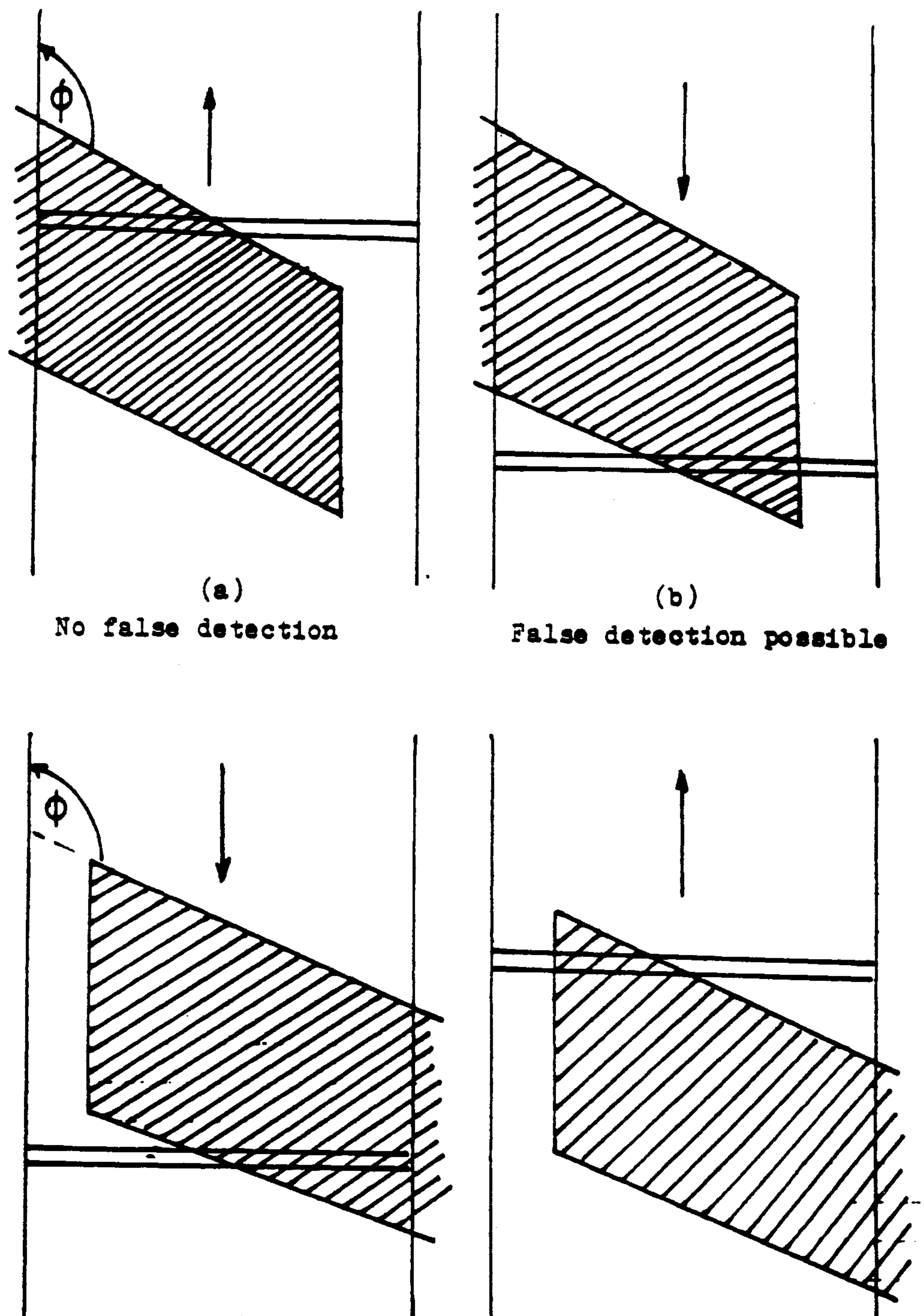


Figure 31. Three shadow situations.



(a)
No false detection

(b)
False detection possible

(c)
No false detection

(d)
False detection possible

Figure 32. Comparison of potential false detection situations due to shadows.

where $V_2 < W+1$. The first median filter must be of order $V_1 - 1$ and the second of order V_2. Thus, all vehicles width width between the indicated limits will be passed by the first filter and blocked by the second, and $| \phi_1 - \phi_2 |$ will equal a pulse of width V and the intensity of this pulse will be the median value of the pulse for ϕ_1.

On the other hand, any shadow, glare or other artifact, in general, starting at either edge at the detection line, will be passed by both filters and then:

$$| \phi_1 - \phi_2 | \approx 0 \tag{16}$$

As mentioned above, this is due to the appendage of k pixels at both ends of the detection line for both filters. For a filter with window width K, recall that pulses with width $p \geq (K+1)/2 = k+1$ are passed and pulses with width $p \leq k$ are blocked.

Consequently, the appending of k pixels at both ends, has the effect of passing "pulses" (shadows or glare) with any width, as long as they start at either edge. This becomes clear graphically in figure 33, where we see that if there is, at least, one non-vehicle pixel at each inner edge of the lane and the vehicle width is $V > k+1$, the pulse is passed by filter one ($K = V_{min} + k$), but not by filter two ($K > V_{max} + k$). If there is a shadow at least one pixel long at either inner edge of the lane, then both filters will pass it because both have k+1 pixels with that intensity in their window when centered at the first or the last pixel, respectively.

Examples

Although in a practical case a lane would have a width considerably larger, for the examples below we have assumed a

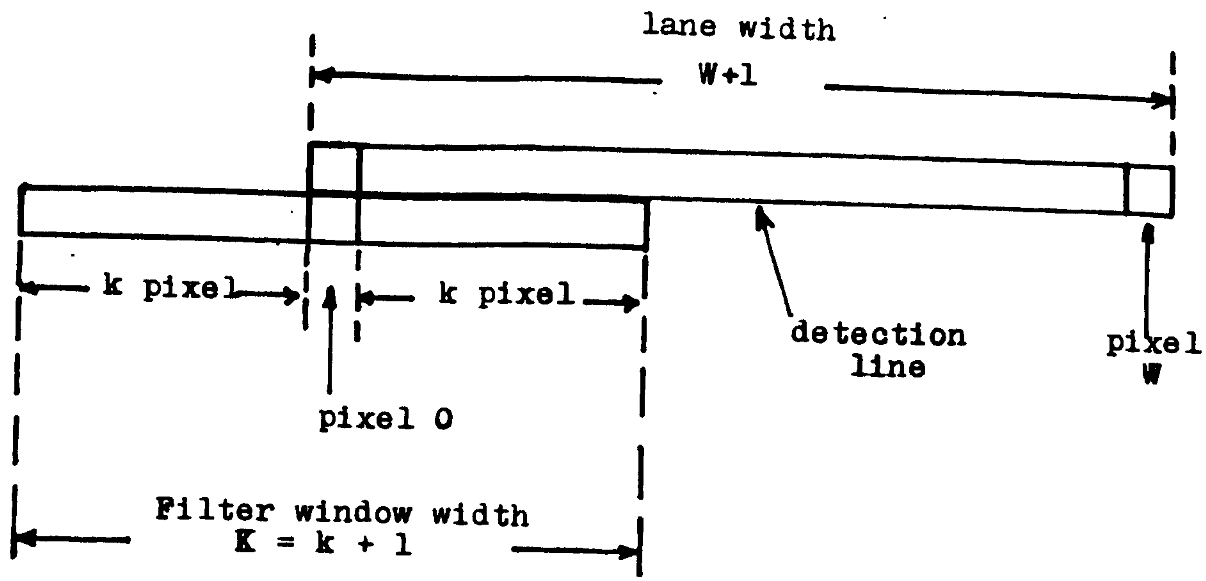


Figure 33. Lane of width W+1 and median filter with window K.

lane with of 18 pixels and car widths from 10 to 14 pixels. A median filter of order K=19 will, hence, pass all vehicles and a median filter of order K=29 will not pass any vehicle within the indicated widths.

Case 1: ten pixels wide vehicle:

a) detected line of gray level values

2 0 0 9 8 7 7 7 9 7 8 8 9 0 0 1 2 0

b) K = 19 median filter output

2 2 2 7 7 7 7 7 7 7 7 7 7 2 1 0 0 0

c) K = 29 median filter output

2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 0

d) absolute value of difference of medians

0 0 0 5 5 5 5 5 5 5 5 5 5 0 1 2 2 0

Case 2: fourteen pixel wide vehicle:

a) detected line of gray level values

2 1 7 8 9 9 8 7 7 9 9 7 9 8 8 7 2 0

b) K = 19 median filter output

2 2 7 7 7 7 7 7 7 7 7 7 7 7 7 7 2 0

c) K = 19 median filter output

2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 0

d) absolute value of difference of medians

0 0 5 5 5 5 5 5 5 5 5 5 5 5 5 5 0 0

Case 3: sixteen pixel wide "object":

a) detected line of gray level values

0 9 8 7 9 9 7 8 7 8 7 7 8 8 7 7 7 1

b) K = 19 median filter output

0 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 1

c) K = 29 median filter output

0 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 1

d) absolute value of difference medians

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

Case 4: eleven pixel wide shadow starting at right edge of lane:

a) detected line of gray level values

0 0 2 0 0 0 2 9 7 8 9 7 8 7 9 9 9 7

b) K = 19 median filter output

0 0 0 0 0 2 2 7 7 7 7 7 7 7 7 7 7 7

c) K = 29 median filter output

0 0 0 0 0 0 2 7 7 7 7 7 7 7 7 7 7 7

d) absolute value of difference of medians

0 0 0 0 0 2 0 0 0 0 0 0 0 0 0 0 0 0

Case 5: eight pixel wide shadow starting at left edge of lane:

a) detected line of gray level values

7 7 9 8 8 7 8 7 1 2 2 2 1 2 0 0 1 0

b) K = 29 median filter output

7 7 7 7 7 7 7 7 2 2 2 2 1 1 1 0 0 0

c) K = 29 median filter output

7 7 7 7 7 7 7 7 2 2 2 2 2 2 1 1 1 0

d) absolute value of difference of medians

0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 1 1 0

In all cases the result is the correct one, as expected.

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