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WIDE AREA DETECTION SYSTEM CONCEPTUAL DESIGN STUDY

FEBRUARY 1978

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16. Abstract

The objective of the Wide Area Detection System (WADS) Project is to determine the technical feasibility of using state of the art imaging (such as television) and processor (such as microprocessor) technology to build an integrated sensor for traffic surveillance on mainline sections of urban freeways. This sensor would be capable of automatically making "area" measurements, i.e. across several lanes as well as along the traffic stream in each lane. These measurements, such as lane density, speed, and volume, would be transmitted back to the central control facility by conventional means and a set of WADS sensors would thus be deployed to cover the entire length of the freeway. The freeway image would also be used for surveillance and incident diagnosis. The WADS project consists of two phases: first, a conceptual design study and second, building a "breadboard" operating sensor.

This volume documents the results of the study phase. This includes 1) the functional requirements for the sensor; 2) the survey of applicable imaging and processor technology; and 3) the conceptual design of the breadboard sensor.

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FOREWORD

This report presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, for the Department of Transportation by agreement with the National Aeronautics and Space Administration (Contract NAS7-100).

CONTENTS

I. INTRODUCTION ---------- 1-1

II. FUNCTIONAL REQUIREMENTS ---------- 2-1

TRAFFIC PARAMETERS AND MEASUREMENTS ---------- 2-1

MEASUREMENT OF TRAFFIC PARAMETERS FROM IMAGES ---------- 2-5

USER REQUIREMENTS ---------- 2-6

FUNCTIONAL REQUIREMENTS DOCUMENT - DESCRIPTION ---------- 2-8

REFERENCES ---------- 2-10

III. SENSOR SYSTEM STUDIES ---------- 3-1

IMAGE CHARACTERISTICS AND GEOMETRY ---------- 3-1

View Geometry ---------- 3-1

Resolution ---------- 3-11

Viewing Limits ---------- 3-14

COMMUNICATIONS STUDY ---------- 3-19

PRODUCTION SENSOR COST ANALYSIS ---------- 3-22

IV. IMAGING TECHNOLOGY SURVEY ---------- 4-1

INTRODUCTION ---------- 4-1

VISION THROUGH THE ATMOSPHERE ---------- 4-1

COMPARISON OF IR TO VISIBLE LIGHT IMAGING ---------- 4-12

IR IMAGING TECHNOLOGY ---------- 4-19

Mechanical Scanners ---------- 4-19

Pyroelectric Vidicon Sensors ---------- 4-20

Military and Commercial Developments ---------- 4-20

DESCRIPTION OF AVAILABLE IR IMAGING HARDWARE ---------- 4-21

FLIR ---------- 4-22

Mini-FLIR Systems ---------- 4-22

Probeye ---------- 4-22

AGA Scanner ---------- 4-23

Pyroelectric Vidicon Camera Systems ---------- 4-23

IR Vidicon Camera Systems ---------- 4-24

IR Optics ---------- 4-25

TRADE-OFF CONCLUSIONS, IR VS. VISIBLE IMAGING ---------- 4-25

VISIBLE LIGHT IMAGE SENSORS ---------- 4-27

PRELIMINARY LENS SELECTION FOR WADS ---------- 4-39

SUMMARY ---------- 4-41

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OF POOR QUALITY

V. IMAGE PROCESSING HARDWARE TECHNOLOGY SURVEY ---------- 5-1
INTRODUCTION ---------- 5-1
SELECTION CRITERIA ---------- 5-3
DESCRIPTION OF TECHNOLOGY ---------- 5-7
Features ---------- 5-7
Future Developments ---------- 5-7
WADS APPLICATION SUITABILITY ---------- 5-14
Highway Environment ---------- 5-14
Reliability ---------- 5-14
Cost ---------- 5-15
Flexibility ---------- 5-16
Processing Hardware ---------- 5-16
PERFORMANCE COMPARISONS ---------- 5-18
Performance Parameters ---------- 5-18
Performance Comparison ---------- 5-19
CONCLUSIONS ---------- 5-23
BIBLIOGRAPHY ---------- 5-23
VI. IMAGE PROCESSING ALGORITHM TECHNOLOGY SURVEY ---------- 6-1
SENSOR SELECTION AND SIGNAL DESIGN ---------- 6-1
APPLICABILITY OF EXISTING ALGORITHM TECHNOLOGY TO WADS ---------- 6-2
FEATURE EXTRACTION TECHNIQUES ---------- 6-3
SAMPLING RATE CONSIDERATIONS ---------- 6-4
RESOLUTION CONSIDERATIONS ---------- 6-6
VEHICLE OCCULTATION IMPACT ---------- 6-11
VEHICLE LENGTH AND HEIGHT ESTIMATION ---------- 6-16
SELECTION OF ALGORITHM APPROACH ---------- 6-20
DISCUSSION OF VEHICLE DETECTION AND TRACKING CONCEPT ---------- 6-22
SUMMARY OF ALGORITHM TECHNOLOGY FOR WADS ---------- 6-22
REFERENCES ---------- 6-24
VII. TEST DATA ACQUISITION ---------- 7-1
VIII. BREADBOARD HARDWARE CONCEPTUAL DESIGN ---------- 8-1
INTRODUCTION ---------- 8-1
SENSOR INTERFACE AND BUFFERING ---------- 8-1
CENTRAL PROCESSING UNIT AND MEMORY ---------- 8-4
COMMUNICATIONS INTERFACE ---------- 8-5
LOCAL CONTROL INTERFACE ---------- 8-5

LOCAL TESTING AND SERVICE ---------- 8-5
POWER AND FAILURE MODES ---------- 8-6
BREADBOARD SYSTEM HARDWARE ---------- 8-6
COST ESTIMATES ---------- 8-9
IX. BREADBOARD ALGORITHM CONCEPTUAL DESIGN ---------- 9-1
OVERVIEW OF ALL BREADBOARD ALGORITHMS ---------- 9-1
THE CALIBRATION ALGORITHM ---------- 9-2
THE VEHICLE DETECTION AND TRACKING ALGORITHM ---------- 9-4
Overview of the VDTA ---------- 9-4
Detection of the Vehicle vs. Road ---------- 9-5
Locating Vehicle in the Cross-Lane Direction ---------- 9-8
Locating Vehicle in the Along-Lane Direction ---------- 9-9
Vehicle Length and Height Estimates ---------- 9-10
Initial Signature Extraction ---------- 9-10
Convert Image Elements to Ground Location and Correct for Vehicle Height ---------- 9-11
Signature Correlation and Update ---------- 9-11
THE PARAMETER REDUCTION ALGORITHM ---------- 9-12
THE INCIDENT DETECTION ALGORITHM ---------- 9-12
THE VERIFICATION ALGORITHM ---------- 9-12
SUMMARY OF BREADBOARD ALGORITHM CONCEPTUAL DESIGN ---------- 9-12
X. CONCLUSIONS AND RECOMMENDATIONS ---------- 10-1
XI. DESIGN REVIEW ACTIONS ---------- 11-1
APPENDIX A. FUNCTIONAL REQUIREMENT, WIDE AREA DETECTION SENSOR ---------- A-1

EXECUTIVE SUMMARY

The inductive loop detector has been for many years the most popular vehicle sensor for freeway surveillance applications. Buried in the road surface, it detects the presence of a vehicle passing over it via a change in inductance. That change is processed by roadside electronics into a "vehicle presence" signal. These signals are then interpreted locally at the freeway site (to provide, for example, ramp metering) or, in a large freeway control system, sent over telephone lines to a central location for processing.

Besides vehicle presence, other measurements that detector signals are processed to provide are volume (vehicle counts per hour), occupancy (percentage of time a vehicle is "present"), spot speed (measured by using two closely-spaced loops), and density (estimated from occupancy). In freeway operations these measurements are point measurements — made at one place in one lane. By using a collection of these loop measurements — at various locations on the freeway and across all lanes — transmitted to a central location, one achieves a basic capability to perform the freeway surveillance task.

Loop detectors, however, leave several things to be desired. First, freeway operations personnel cannot "see" what is really happening on the freeway. Is traffic moving smoothly? Is there an incident? If so, what kind? Some sort of imaging surveillance would be highly desirable. Second, traffic engineers would prefer to have additional lane parameters measured. Space mean speed and density are key measurements in traffic control, and they are made on an interval, rather than a point, basis. Thus, sensor coverage over a freeway section (i.e., a two-dimensional area) that would provide both images and traffic parameter measurements would greatly enhance the usefulness of traffic surveillance.

In recent years, advances in electronics technology have brought about a rapid miniaturization of components via solid-state manufacturing processes. The products produced by such processes, e.g., transistors and integrated circuits, are amenable to mass production and have inherently higher reliability than products containing tubes or relays. From the cost point of view, dramatic economies of scale are evident in this area. Prices of established products have dropped significantly as volume has expanded. Imaging electronics now has a class of solid-state units; microprocessors are, of course, solid-state devices.

Can this body of technology be used to perform the desired type of area surveillance? The objective of the Wide Area Detection System (WADS) Project is to determine the technical feasibility of developing an imaging sensor which will automatically measure traffic parameters on mainline sections of urban freeways.

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Project Description

The project has been divided into two main activities: a conceptual design study phase and a breadboard model phase. The conceptual design study's objective is to lay the necessary groundwork for the selection of the sensor. The functional requirements for the sensor were determined by studying how it would be used in a freeway operating environment. The relevant technology — both image sensors and image processors — were studied to identify the best candidates for the design. A conceptual design activity then followed to determine the most appropriate design of a breadboard model to demonstrate the key WADS performance features. Finally, a preliminary estimate was made, looking to the future, of the characteristics of a 1980-era production sensor, both in cost and performance. This report presents the results of this conceptual design study activity.

After the design review, held at the conclusion of the first phase, and upon receipt of FHWA approval of the conceptual design, the project will then proceed to the breadboard phase. A "breadboard" model in research and development projects (such as WADS) customarily denotes the first hardware unit that shows the essential performance features required by the project. In comparison with the eventual production unit, a breadboard model is not properly designed mechanically; it doesn't have any "frills" in its performance; and it is not necessarily made from the same electronic hardware pieces. A breadboard model is supposed to show that a concept works; the remaining work to develop the production unit can be viewed as product design and engineering.

The WADS breadboard model will be designed, in detail, to meet the important performance requirements determined in the design study. It must be portable and capable of freeway site operation. It must have considerable functional flexibility to allow for development and change in the processing algorithms. The breadboard model will be fabricated and checked out in the laboratory with simulated inputs, such as recorded videotapes of freeway scenes. After satisfactory checkout, it will be taken to a local California freeway site and tested. Results will be compared against "ground truth" data provided by loop detector outputs. The total project will then be documented in a final report, which will include an appraisal of the feasibility of commercial application of the WADS concepts.

Summary of Conceptual Design Study Results

In the functional requirements study, a significant point that emerges from the examination of view geometry is that no single fixed view satisfied all needs. Low mounting heights (25 feet (7.62 meters)) produce good near-field views of the road, but lanes merge quickly into the far field (1/4 mile (0.4 km)), limiting resolution for surveillance. In addition, low mounts make viewing of the other side of the freeway (i.e., the opposite direction of flow) difficult. High mounting heights (e.g., 100 feet (30.5 meters)) would enable a more

uniform use of the sensor resolution and allow coverage of both sides of the freeway; however, mountings for these heights are more expensive and are often undesirable from an environmental standpoint. Communication with freeway operations personnel indicates that a pan/tilt/zoom capability is very desirable, perhaps mandatory. However, measuring traffic parameters and simultaneously moving the camera to diagnose an incident are not compatible operations. Hence the camera should have two separate modes of operation: an operator-controlled mode, in which the camera can be moved by a remote operator, and a traffic parameter measurement mode, in which the camera is "fixed" in position (perhaps by a mechanical detent) and looks at a broad view of the freeway section. In an alternative approach, the WADS may use two cameras — one with a pan/tilt/zoom capability, and the other stationary, and dedicated to traffic flow measurements. Because of resolution and processing difficulties, traffic flow measurements can only be made on the near-field part of the image. This "measurement test section" is estimated to be 200-500 feet (61-152 meters) along the roadway.

In the image sensor (i.e., camera) technology survey, three approaches to imaging were studied: conventional vidicons, solid-state visible-light sensors (such as charged-coupled devices), and infrared sensors. All three, in their current state of development, are able to provide high resolution, high quality, and good sensitivity range imaging for the WADS application. All three behave similarly in degraded imaging in bad weather. Infrared offers the advantage of being sun "blind", i.e., day and night images are very similar and the camera can be pointed at the sun without incurring damage. However, the cost of infrared devices ($15,000 and up) is currently prohibitive. Therefore, because the different cameras, to a first order approximation, performed so similarly, the choice among them focused on the issue of cost. Silicon-diode array vidicon technology was chosen for the breadboard model, with CCD technology a probable choice for the 1980-era production unit if the prices continue to drop.

The image processing technology survey investigated both the hardware and software required for the application. In the hardware study the standard set of image processing components — analog-to-digital converters, buffers, minicomputers, and microprocessors — were evaluated. The chief conclusion is that microprocessors, via chip sets built up into the processor, are fast enough to do the job, but are not flexible enough or software-convenient enough to be used for the breadboard mode. Since it is expected that considerable software development work for the processing algorithm will be done with the breadboard model, a minicomputer will be used. For the 1980-era production unit, however, it was concluded that such microprocessors would be an excellent choice. Other hardware components needed for the image processing system are available, and costs are dropping.

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In contrast to the relatively mature state of the hardware technology, the technology of the software, i.e., the image processing algorithm, is not well developed. The human eye and brain together form a truly amazing image processor. What appears simple for the human to do is typically difficult or impossible to do in a machine. The algorithm for the WADS application must first detect an object, which is assumed to be a vehicle, and then observe it in some fashion over an interval of road to take measurements. It must reject shadows of the cars that fall in adjacent lanes. It must work in bright sun, at low sun angles, and at night with vehicle lights on. The eye can easily discern when one vehicle is partially blocked by another vehicle closer in view. An image processor, however, has great difficulty with the "merged vehicle problem." It has been recognized from the beginning that algorithm development is the cornerstone of a successful demonstration of the WADS concepts, and careful attention has been paid to this matter during the study phase.

To understand the characteristics of the image, a number of videotapes were taken at local freeway sites under different lighting and weather conditions. Common features of the images were sought, to ease the processing job in various ways. Many algorithm approaches were evaluated on paper; a few were tried in the laboratory, operating on the videotapes. What has emerged from this work is a tracking-class algorithm that appears to show great promise.

The process employs a camera pointed at traffic moving downstream, away from the sensor. The vehicles enter the field of view at the bottom of the image, in the near field. They are detected as they enter, since vehicles are at their maximum separation in the near field and hence the "merged vehicle" detection problem is minimized. The vehicles are then tracked out several hundred feet and measurements taken in this "test section". If successful, this approach would provide vehicle trajectory information, in-lane and across lanes, automatically in real time — this in addition to measuring volume, space mean speed, and density over the test section. The algorithm has many details yet to be worked out, but it appears to offer very good performance at a reasonable computational burden.

After the algorithm development work described above had been completed, a functional requirement specification for the sensor was written. It sets forth requirements for the operating environment, performance, installation, and other matters associated with operational use of a WADS production unit (see Appendix A).

The proposed conceptual design of the breadboard model reflects the above (and other) results. Its configuration is very flexible in the accessing and processing of picture samples. It has a full field buffer random access memory and a fast minicomputer with a good software package. These features will greatly facilitate the algorithm's development. As mentioned previously, a silicon-diode array vidicon was chosen as the camera for the breadboard mode.

On April 28, 1977, the results of the conceptual design study were presented to the Federal Highway Administration, Office of Research at a design review. In addition to the FHWA reviewers, three outside experts — one each from the image sensor, image processing, and freeway operations fields — attended the review and critiqued the study results. Many important comments and suggestions were made at the review. Although there appeared to be no basic disagreement with the breadboard design approach, several matters were judged to merit further investigation. These included the effect of sway (wind and vibration) on the sensor's performance, the benefits and costs of 50-100 foot (15-30 meters) camera heights, and the merits and costs of using two cameras (one fixed, one pan-tilt-zoom) as another solution to the problem created by the fact that a single camera cannot simultaneously perform both traffic measurement and operator-controlled surveillance. The details of the design review are discussed in Section XI of the present report.

Conclusion and Recommendation

It is believed that the conceptual design study has identified the key technical factors relating to the feasbility of the WADS sensor concept. A comprehensive study of this matter has been made, and the algorithm has been identified as the most challenging aspect of the program. Initial development of an algorithm concept has been carried out, and its mechanization in hardware and its performance appear very promising. At the conclusion of the design review, it was recommended that the project go forward into the breadboard phase. The breadboard model would answer many important detailed questions about the performance and hardware needed in a production sensor, and would contribute to other companion projects in highway research via its use as a research tool.

SECTION I

INTRODUCTION

Urban freeway surveillance and control, in a variety of ways, has been in use for many years. It seeks to achieve smooth, efficient, and safe operation of freeways, particularly during peak demand periods. The elements of an operating system include a traffic surveillance network, which measures the level and status of traffic flow on all the freeways being controlled; a central control center, manned by operations personnel who use this traffic information to decide how to optimize flow and respond to incident situations; and the control mechanisms--ramp meters, motorist advisory signs, emergency vehicles, and so on--which the control center uses to effectuate its control of the freeways.

It is the freeway surveillance part of this system that is the focus of the Wide Area Detection System (WADS) project. In particular, the feasibility of a new technical approach to traffic surveillance will be studied: direct processing of images (e.g., television pictures) of freeway traffic.

Everall has comprehensively described the many types of sensors used in surveillance.* Most are individual vehicle detectors, measuring the presence of a vehicle at a particular point in the roadway. The inductive loop is a good example of this kind of "point" sensor. Television is another kind of sensor, one that gives "area" or two-dimensional coverage of the roadway. Television has been used in several cities for surveillance and incident detection. It provides the operator with actual views of traffic, but the images are not quantitative: a computer cannot automatically extract vehicle counts or other such data. Vehicle detector sensors, on the other hand, are quantitative but the traffic "picture" that emerges from a collection of vehicle detectors falls short of an actual view of the scene. The Wide Area Detection System project seeks to bridge this gap by investigating whether an image sensor can be made quantitative — that is, can generate traffic measurements — by automatic processing of the images.

In order to investigate the feasibility of the WADS concept, the project has been divided into two main activities: the conceptual design study phase (which is the subject of the present report) and the breadboard phase. The objective of the conceptual design study is to lay the necessary groundwork for the design of the sensor. The functional requirements for the sensor were determined by a study of how it would be used in a freeway operating environment. The relevant technology — both image sensors and image processors — were studied to determine the

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*P. F. Everall, Urban Freeway Surveillance and Control - The State of the Art, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., June 1973.

best candidates for the design. A conceptual design activity then followed, to determine the most appropriate design of a breadboard model to demonstrate the key WADS performance features. Finally, a preliminary estimate was made, looking to the future, of the characteristics of a 1980-era production sensor, both in cost and performance.

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This report covers the results of the conceptual design study and the design review held at the end of that phase.

SECTION II

FUNCTIONAL REQUIREMENTS

TRAFFIC PARAMETERS AND MEASUREMENTS

Vehicular traffic depends on many factors. Some are functions of vehicular performance and highway design while others are indications of driver behavior.

Traffic, as a flow phenomenon, is commonly characterized by volume, speed, and density measures. There are at least 17 other parameters which are also used to define different aspects of traffic flow (Ref. 2-1). Many of these are derived from combinations of the three basic measures or by averaging over time and distance. Some are related to designed and actual roadway conditions and capacities. Since most of these other measures are analytically related to the three basic quantities, they can be derived by computer-programmed algorithms.

The three basic variables are defined as follows:

(1) Volume is the accumulated count of vehicles which have passed a given point in some time. The unit for volume is vehicles/lane-hour. Volume is more akin to the flow of quanta than to capacity, which the name implies. The appropriate volumes multiplied by the number of lanes and 24 hours yields average daily traffic.

(2) Speed is a very complex quantity in traffic flow, not in concept but because sensors external to the vehicle typically provide only time-averaged or space-averaged measures of speed. The driver receives continual data concerning the rotational velocity of one of the wheels or drive line of his car. An outside observer, however, can determine the speed of the car only by the elapsed travel time over a short distance (speed trap) or by the doppler shift of a reflected radar or ultrasonic acoustic wave. The doppler measurements are closest to the instantaneous speed measured by the speedometer, and this speed is called "point speed" or "spot speed." The speed measured by the transit time over a distance is called "space speed." Both are measured in distance divided by time (e.g., mph, kph, fps, etc.). Where the differences of the two concepts of speed show up is in the averaging of speeds. The average of point speed or point mean speed or time mean speed, as it is also called, is the arithmetic mean of the observed speeds. The space mean speed or harmonic mean speed is the reciprocal of the arithmetic mean of the travel times divided by the distance. To convert from one to the other requires some knowledge of the variance of the speed being measured (Refs. 2-2, 2-3). The two means are equal only when the variance is zero (all cars travel at the same speed); otherwise the point mean speed always yields a higher value than space mean speed.

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(3) Density is also known as concentration and is a measure of the number of vehicles per unit length of roadway, e.g., vehicles/lane-mile. It is the quotient of volume divided by point mean speed if derived from observations of a short length over a long time. Otherwise it is the quotient of the number of vehicles physically present in a long length of roadway divided by the length. The latter measure is obtained by a short time observation of a long length such as by an aerial photograph.

Since the volume, density, and mean speed are reflections of the aggregate motion of individual units (vehicles) and are somewhat like fluid flow, many attempts have been made to develop functional relationships between the three flow parameters. The relationship is primarily statistical rather than functional. A typical curve representing a good fit to reality is shown in Figure 2-1. This curve of volume versus speed is quite similar to Greenshield's parabolic curve developed in the 1930s. The top part of the curve presented here is determined by a combination of legal speed limit, driver ability, and vehicle performance as well as highway design. As the curve approaches the maximum flow or volume, there is not a great decrease in speed. Once past the maximum flow, the speed drops and becomes somewhat indeterminate, since there is incipient congestion. Speed and volume then continue to decrease as the congestion increases.

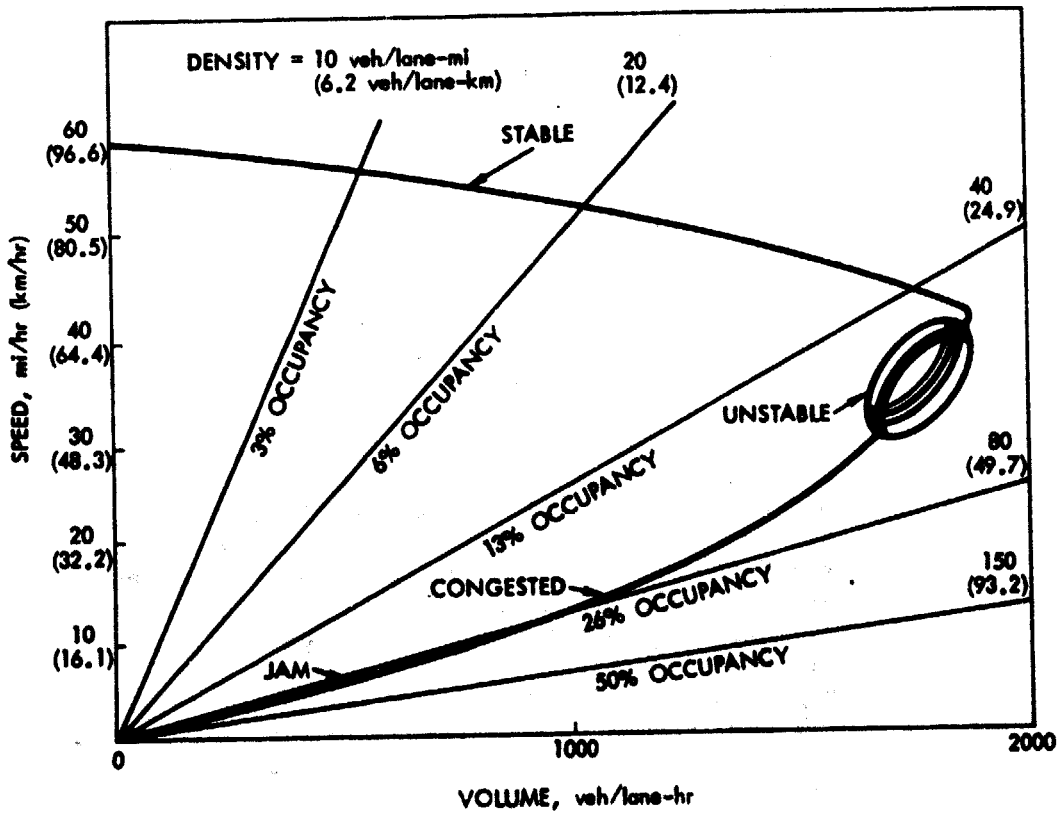

Figure 2-1. Volume vs. Speed

There are several conditions of flow described by different portions of the curve. The top part represents free, unimpeded flow at volumes much less than maximum. As the flow approaches maximum capacity, speed drops to about two-thirds of the maximum. Once past this part of the curve, speed and volume decrease together while density increases and incipient congestion occurs. Below this part of the curve, congestion is severe and, still lower, the traffic is jammed.

The density of vehicles in each lane-mile for the various parts of the curve are indicated by the numbers superimposed above the curves. The density relationship to speed and volume used here is obtained by averaging over long observation periods and therefore the density is equal to volume divided by speed.

As stated before, the traffic flow curve represents a best fit to real data. A particular curve may be quite accurate in describing the flow on one part of a highway, whereas a curve with similar shape but greater (or less) maximum volume and speed may describe another portion of the road more precisely.

Figure 2-2 shows traffic flow versus density. In this presentation, the radials of constant slope are the different speed values. Again the short distance relationship is used. Similarly, the radials of constant slope represent density of traffic in Figure 2-1. The lines of constant density are derived from the speed-volume relationship alone and no assumption as to the uniformity of spacing of actual traffic should be made.

Occupancy is a substitute measure for density and is a consequence of using a point (or very small area) instrument as a measuring device. Occupancy is accepted as the ratio of the time some vehicle is present over the point of measure to the total time. For constant velocity in the neighborhood of the point, this ratio could be stated as the fraction of roadway length occupied by vehicles. This then corresponds to density measured over a short length, but only if this aggregate length of vehicles is considered to be made up of a series of uniform length vehicle units. Density is usually derived from occupancy in this manner. Density is really independent of the traffic mix of passenger cars, trucks, buses, RVs, etc. The occupancy values shown in Figure 2-1 assume an average vehicle length of 17.6 feet (5.36 meters). Others have used 19, 17.3, and 20 feet (5.79, 5.27, and 6.1 meters) and justified the choice on the basis of statistical methods. The value 17.6 feet (5.36 meters) was chosen because it yields a maximum permissible density of 300 (a nice round number) vehicles per mile (186.4 vehicles per kilometer) under bumper-to-bumper conditions and has no other justification.

It can be seen from Figure 2-1 that there is a substantial speed variation for little change in volume near the maximum volume of say 2000 vehicles per hour. Conversely, the partial derivative of volume versus speed is least at the maximum volume. On the other hand, the density or occupancy change is substantial near maximum volume as can

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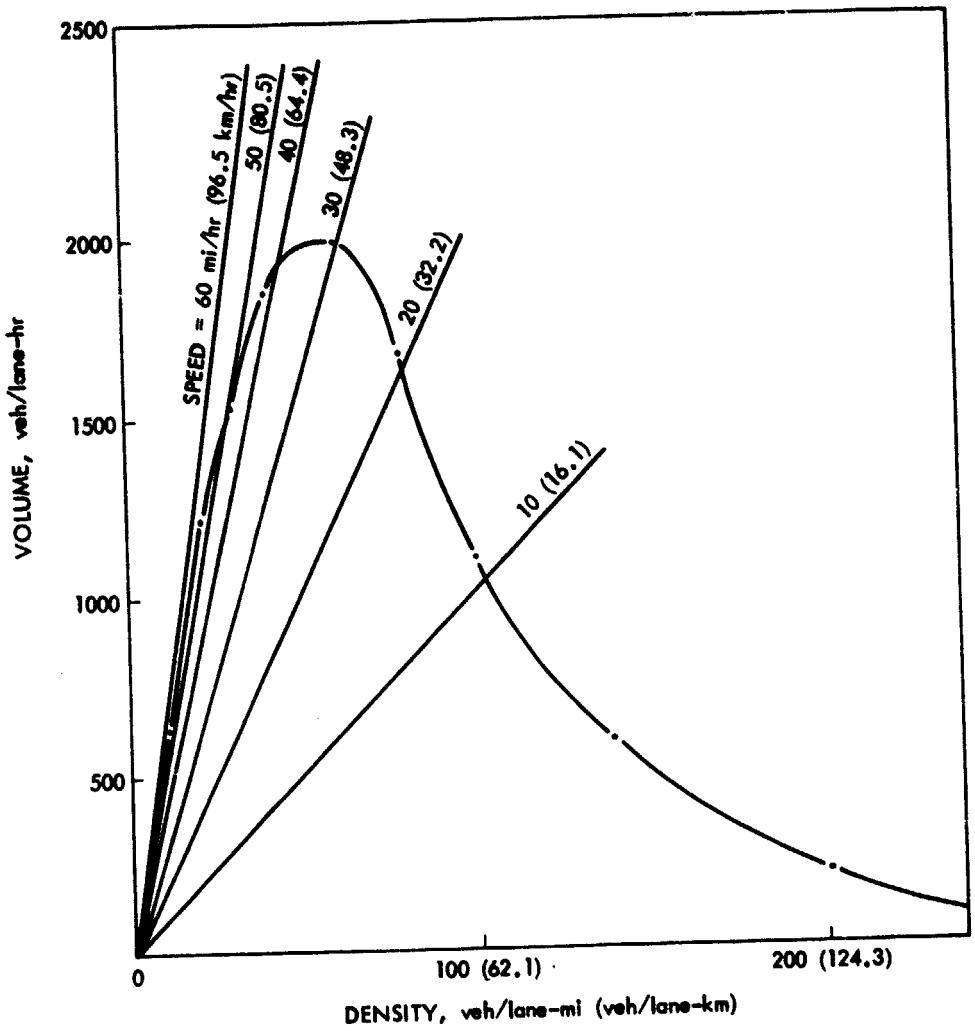

Figure 2-2. Volume vs. Density

be seen in Figure 2-2, more than doubling (from 30 to 70) between the two 1500 vehicle per hour intercepts, for example. Therefore, if the intent is to maximize volume based on information derived from the change in measurements, then density (occupancy) seems to be a more important measurement than speed as it is a more sensitive indicator.

Neither density or occupancy can be measured at any instant of time with a point detector. Current practice, as stated, is to calculate occupancy from the ratio of the time that a vehicle presence is detected by a point sensor (loop, magnetometer, flux-gate, etc.) to the total time. The vehicle count is determined from the sum of transitions from vacancy to occupancy which, together with the speed derived by estimate, leads to a density value, as was shown before. Since the density measure is derived from occupancy, little use is made of it and occupancy is the more used quantity. In the WADS, however, it may be possible to actually count the vehicles in the entire field of view, achieving a true instantaneous density measure.

MEASUREMENT OF TRAFFIC PARAMETERS FROM IMAGES

The traffic parameter information to be gained from a single image is limited to spacing of the vehicles, density, and perhaps the traffic mix. A succession of images allows other parameters to be derived, principally from the change of position of each vehicle. A series of vehicle displacement versus the time intervals of the images allows a space velocity for each vehicle to be ascertained which then allows space mean speeds to be determined. Changes in the speeds can then yield accelerations and the acceleration noise parameter.

The derivation of traffic parameters from a succession of aerial photographic images has been studied extensively (Ref. 2-4). A very basic problem has been the rectification or resectioning of successive pictures so that fixed reference points can be established and distances adjusted.

Translations, rotations, and scale changes from one aerial photograph to the next are needed because of the changes in position of the airplane or helicopter used in taking the pictures. These adjustments are avoided in systems such as WADS, where the camera is rigidly positioned. A constant field of view provides a constant coordinate system, which simplifies the vehicle displacement measurements and vehicle trajectory determinations.

The counting of discrete vehicles in an image requires an algorithm with substantial complexity (cf. Section IX). The count of vehicles in a given length of freeway from one image provides a density measure. An alternate method, though less accurate, is to count the vehicles entering and leaving the given length or test section. The difference in accumulated counts of entering and leaving vehicles is the number in the test section. This residue of vehicles also provides a density measure over the test section. The requirement in this technique is that every vehicle must be counted. Any error in counting will be propagated as a continual density error as there is no means to correct the counting. Startup or reinitializing of the counting necessitates that the test section be empty for the time necessary for vehicles to traverse the test section. Many images are involved in the counting process even when the test section is empty. For densities in the 25 to 100 vehicles per line-mile (15.5 to 62.1 vehicles per lane-kilometer) range and a 200-foot (61-meter) observed distance or test section, there should then be only 1 to 4 vehicles in the observed distance on each lane. The traverse time for this distance is on the order of 5 seconds or less for speeds corresponding to the densities chosen. As stated before, in the density determination made by differencing counts there is the requirement that all vehicles be counted and that some means of determining, either by a large gap or pattern of vehicle lengths, when particular vehicles have left the area. Once the counting process has been initialized, a continual measure of density can be provided. The extrapolated values of density with 1 to 4 vehicles in the test length for this technique would be 26, 52, 78, and 104 vehicles per lane-mile (16.1, 32.3, 48.5, and 64.6 vehicles per lane-kilometer) as the test section is about 1/26th of a mile (1/16th of a kilometer). The average

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density measure would therefore be no more accurate than one half the least quantization interval or 13 vehicles. The tracking algorithm, on the other hand, provides a definition of the shape (size) of the vehicle as it enters the field of view. Therefore this algorithm can provide fractional values of area of the vehicle shapes which may be entering or leaving the test section. By combining these fractional "cars" with the whole cars inside the test length, an extrapolated value of density can be had which may have a much smaller uncertainty.

The velocity range defined according to Fig. 2-1 from the foregoing density range of 25 to 100 vehicles per lane-mile (15.5 to 62.1 vehicles per lane-kilometer) is from 10 to 60 miles per hour (16 to 96.6 kilometers per hour). The imaging sensor with tracking algorithm should accomplish measurements down to zero miles per hour. Measurements can also be accomplished satisfactorily at much faster vehicle speeds and 80 miles per hour (128.7 kilometers per hour) was chosen as an upper limit. This speed capability allows isolated speeders to be detected. Such detections might be considered as incidents requiring notification of law enforcement agencies.

The vehicle density range to be measured was limited to 150 vehicles per lane-mile (93.2 vehicles per lane-kilometer), corresponding to about 50% occupancy. This limit was imposed because the shortest cars, imported convertibles, tend to merge or overlap in the field of view at the end of the test section when the spacing equals the vehicle length. Taller cars merge at lesser distances. Isolated long tow-bar trailers which are quite common in the sand, gravel, and concrete trade have separations between truck and trailer comparable to the lengths of imported vehicles. It therefore seemed unnecessary to complicate this measurement by demanding greater performance than that provided by a 50% upper limit.

The vehicle count range was set substantially higher (3000 vehicles per lane-hour) than most flow curves indicate (~2200 vehicles per lane-hour) in order to handle sporadic bursts of very high flow. In addition, a trend toward very small cars for various reasons would cause greater volumes in the future than with the present-day traffic mix.

USER REQUIREMENTS

The ability to observe representative images of the traffic flow while also measuring flow parameters seems to be a widespread desire of freeway operating agencies. The visual aspect has received much attention since it is state-of-the-art technology (i.e., television). Several cities have implemented the installation of closed circuit television for surveillance of critical areas. Dallas and Baltimore (Refs. 2-5, 2-6), which have TV installations, also use loops and magnetometers to measure the flow parameters. Los Angeles has an extensive installation of loops and is planning a television installation along one freeway.

No sensor or system of sensors currently exists that can both measure the traffic and also provide images. If such a sensor were

available, combining both features, the expressed opinion from a sampling of the traffic control community was that it should provide performance equal to that provided by loops and TV separately.

The television imaging requirement is not for mere casual observation but for the visual inspection of incidents. The imaging requirement usually stated was that incidents (stopped vehicles) be sufficiently discernible to permit a preliminary determination of what type of aid should be dispatched. It was recognized that, during the observation of incidents, traffic parameter measurements probably could not be made unless multiple cameras were used.

Traffic flow parameter measurements can be made on only one side (direction) of the freeway because of available fields of view and other geometrical considerations. (These factors are explored further in Section III.) In addition, since the tracking algorithm can most easily "pick up" a vehicle when it is largest, i.e., when it enters the bottom of the field of view, the sensor will view the downstream portion of the traffic. The field of view encompasses all lanes and should therefore be able to measure the parameters of vehicle volume, speed, and density of all lanes. This is substantially more than can be accomplished with single loops (or magnetometers) in each lane. Multiple speed traps implemented in each lane would be required with point detectors to duplicate the WADS parameter performance.

Current practice is to space the clusters of loops about 1/4 to 1/2 mile (0.4 to 0.8 kilometers) apart and the WADS should be similarly spaced. For traffic flow measures, the WADS is focused on a 200-foot (61-meter) downstream section of freeway, and it is unlikely that most of the incidents will be concentrated there. The WADS imaging performance should therefore be such that vehicles be discernible to the limit of spacing. This requirement dictates that variable focal length or zoom optics be used to get a large image size of a vehicle at maximum range. Since the field of view is greatly reduced by high magnification optics, pointing capability or pan and tilt must also be provided. The pointing ability can then allow upstream as well as downstream viewing of incidents and may even provide views of opposite-direction lanes and frontage roads and ramps. The ability to view an incident from two different directions should provide increased assessment capability.

Another user requirement was that existing structures be used wherever possible for mounting the WADS. Structures such as sign bridges, either truss or cantilevered, or overpasses are preferred because of the rigidity. Luminaires were not thought to be appropriate because of possible torsional vibration and sway in strong winds. This needs to be investigated further before light post use is ruled out.

The variety in configuration of mounting sites implies that universal or adaptable mounting hardware be provided for the image sensor of the WADS. The mounting sites also have implications as to the servicing and maintenance of the WADS. Because of the hostile environment of freeways with respect to service and maintenance activities, the normal procedure is to remove and replace hardware, with repairs being accomplished in a service facility. The image sensor of the WADS should

be removable by one person without heavy lifting equipment; the walkways on sign structures may be an aid in this respect. Pole mountings, on the other hand, will require that a cherry picker or the like be used in WADS maintenance.

Sign mounting sites tend to dictate a height-above-pavement for the WADS of about 25 feet (7.6 meters). The views obtainable from this height and higher locations are explored in Section III.

In addition to the requirement that the system be easy to maintain, parts standardization, accuracy, and reliability are also important. The accuracy requirement usually reflects the experience with loops or other point detectors, for which errors are typically 3 to 5% of the full scale measurement. Reliability refers to the service interval or mean-time-to-failure of the WADS. No fixed time between failures was stated as a minimum requirement, but since the WADS is powered continuously, a mean-time-between-failures of at least 10 thousand hours should be a design goal.

FUNCTIONAL REQUIREMENTS DOCUMENT — DESCRIPTION

The functional requirements (FR) document for the WADS (presented herein as Appendix A) attempts to codify the various features needed to perform both the incident imaging and traffic parameter measurement functions. It attempts to tell what tasks WADS should do, and how well, without being specific as to how the tasks are to be done.

The functional requirements were developed after a study of the constraints of the highway environment and a survey of user requirements. Since these constraints and requirements will be further explored in the course of the program, the FR document will undergo change. The FR document presented in Appendix A is therefore preliminary and represents a design goal for the prototype model that will be developed following the evaluation of the breadboard model.

The format of the FR document is patterned after that widely used for hardware systems and subsystems and is somewhat different from the general and specific conditions documents used in highway work.

Part 1 of the FR broadly defines the tasks of the WADS.

Part 2 identifies, by reference, other documentation that is a part of the requirement. At present, only the NEMA Publication No. TS1-1976, Traffic Control Systems (Ref. 2-7) is cited. This document was selected as being applicable to the WADS because it addresses systems which are functionally similar to the WADS. The NEMA document also defines the electrical and physical environments in the highway transportation art. Many traffic-control terms and testing methods are presented, and duplication in the WADS FR document is thereby avoided. This section of the FR document will probably expand as other manufacturing process and control documents establishing how WADS are to be built are included. Handling, mounting, and maintenance documentation will also be added.

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Part 3, which is the functional description, is the central part of the document; it describes the tasks to be performed. It identifies the direct and derived parameters to be measured and gives a qualitative definition of each. The mobility and other functional features needed for incident viewing are specified in this part. The functional elements which make up the WADS are also presented.

Part 4 specifies the interfaces of the WADS. These include provisions for bringing the electrical power and electric signals in and out of the WADS. The mechanical mounting philosophy and choice of mounts for viewing and other considerations are described.

Part 5 is the definition of how well the WADS must perform. The performance goals are presented in two tables, one for traffic parameter measurements and the other for incident imaging. These tables show the quantitative values for the various performance features required of the WADS.

Part 6 is a preliminary description of the physical characteristics desired for the WADS. These include the weight and volume limits as well as the environmental conditions for the WADS. Included in this part are modified excerpts from NEMA concerning the electrical and physical environmental tests and the methods of performance of the tests.

Part 7 delineates some safety and special considerations that must be observed. This section will later include transportation, packaging, and handling requirements.

Part 8 relates to certification of the WADS. This part will eventually contain formal sign-off procedures which will establish that each WADS will perform as required.

REFERENCES

2-1. Traffic Control Systems Handbook, Federal Highway Administration, Washington, D.C., June 1976.

2-2. Traffic Flow Theory -- A Monograph, Special Report 165, Transportation Research Board, National Academy of Sciences, Washington, D.C.

2-3. Oppenlander, Joseph C., "Sample Size Determination for Travel Time and Delay Studies," Traffic Engineering, Sept. 1976.

2-4. A Study to Determine the Feasibility of Development of an Area Traffic Surveillance and Control System, Final Phase 1A Report, General Electric Co., prepared for the Federal Highway Administration PB183848, Feb. 1969.

2-5. Servey, Thomas E., "A Traffic Control System in Keeping With the Times," Traffic Engineering, July 1976.

2-6. Erdman, John W., and Barnfield, Curtis L., "Baltimore's Freeway Surveillance and Control System," Traffic Engineering, July 1976.

2-7. Barker, John L., "NEMA Standards for Traffic Control Systems," Traffic Engineering, Sept. 1976.

SECTION III

SENSOR SYSTEM STUDIES

IMAGE CHARACTERISTICS AND GEOMETRY

View Geometry

The user request that existing sign bridges or similar structures be used for WADS implies a height-above-pavement limit of about 25 feet (7.6 meters). It is feasible to use higher mounts near the roadway, especially in metropolitan areas or on depressed freeway sections. In order to depict what the WADS sensor will see, diagrams representing several views were generated. The views selected were of a straight portion of one side of a freeway. Figure 3-1 depicts the locations of WADS relative to the roadway. Three heights were selected for comparison: 25, 35, and 50 feet (7.6, 10.7, and 15.2 meters). Views from a central location above the lanes as well as those obtained by looking from the roadside were developed. A third variable chosen was the horizontal and vertical view angles which fix the approximate focal-length-to-sensor-diagonal ratio. A ratio is presented rather than a focal distance to allow comparison with other lens/sensor combinations which would yield the same ratios. The focal length ratios are approximate, since the vertical angle was halved for each successive view in each figure; the focal lengths are proportional to the tangents of these angles.

Figures 3-2, 3-3, and 3-4 depict the views obtained from an image sensor centered over the roadway at 25, 35, and 50-foot (7.6, 10.7, and 15.2-meter) heights with various vertical angles. The views are of four 14-foot (4.27-meter) lanes and two 10-foot (3.0-meter) shoulders (or medians). In all cases the farthest distance is about 1/4 mile (1320 feet) (0.4 kilometer) at the top of the view.

Figures 3-5, 3-6, and 3-7 are views from the same heights with the same vertical angles of the same roadway when the image sensor is placed over the right edge of the shoulder and pointed parallel to the roadway with the top edge of the view at 1/4 mile (0.4 kilometer). The same three heights of 25, 35, and 50 feet (7.6, 10.7, and 15.2 meters) and the same four focal lengths as before are used. The near point distance corresponding to the bottom edge of the view is the same as in the corresponding views centered over the roadway. The distance at which the left edge of the number one lane enters the view is almost always farther than the near point and, in several height/focal length combinations, is even farther than the midpoint or aiming distance. The longitudinal resolutions for these road edge views are almost exactly those of the views with the sensor centered over the lanes.

Figures 3-8 and 3-9 represent the views of the roadway obtained when the maximum range is 500 feet (152.4 meters) from a sensor height of 25 feet (7.6 meters). It can be observed that, although nearer portions of the roadway might be observed, the position in the view where all lanes can first be seen has merely moved up in the view.

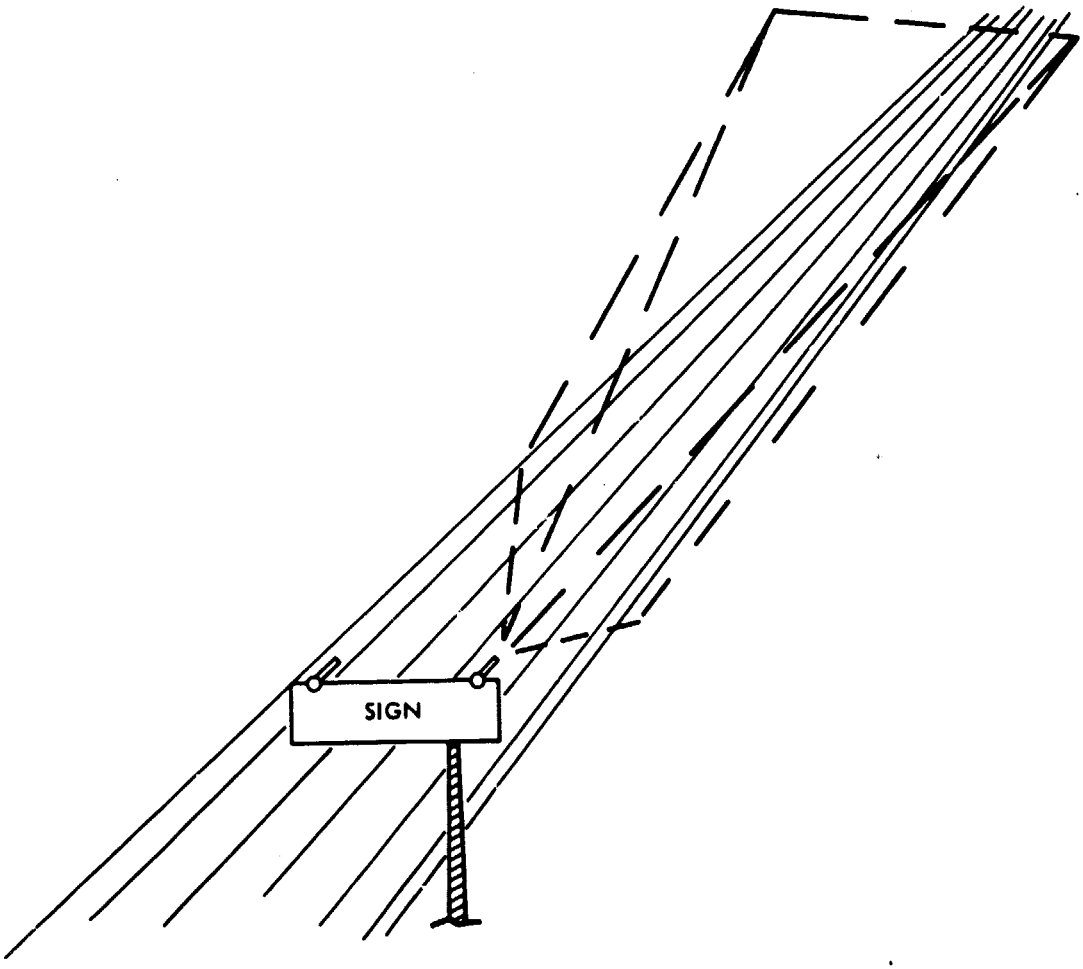

Figure 3-1. WADS Viewing Positions

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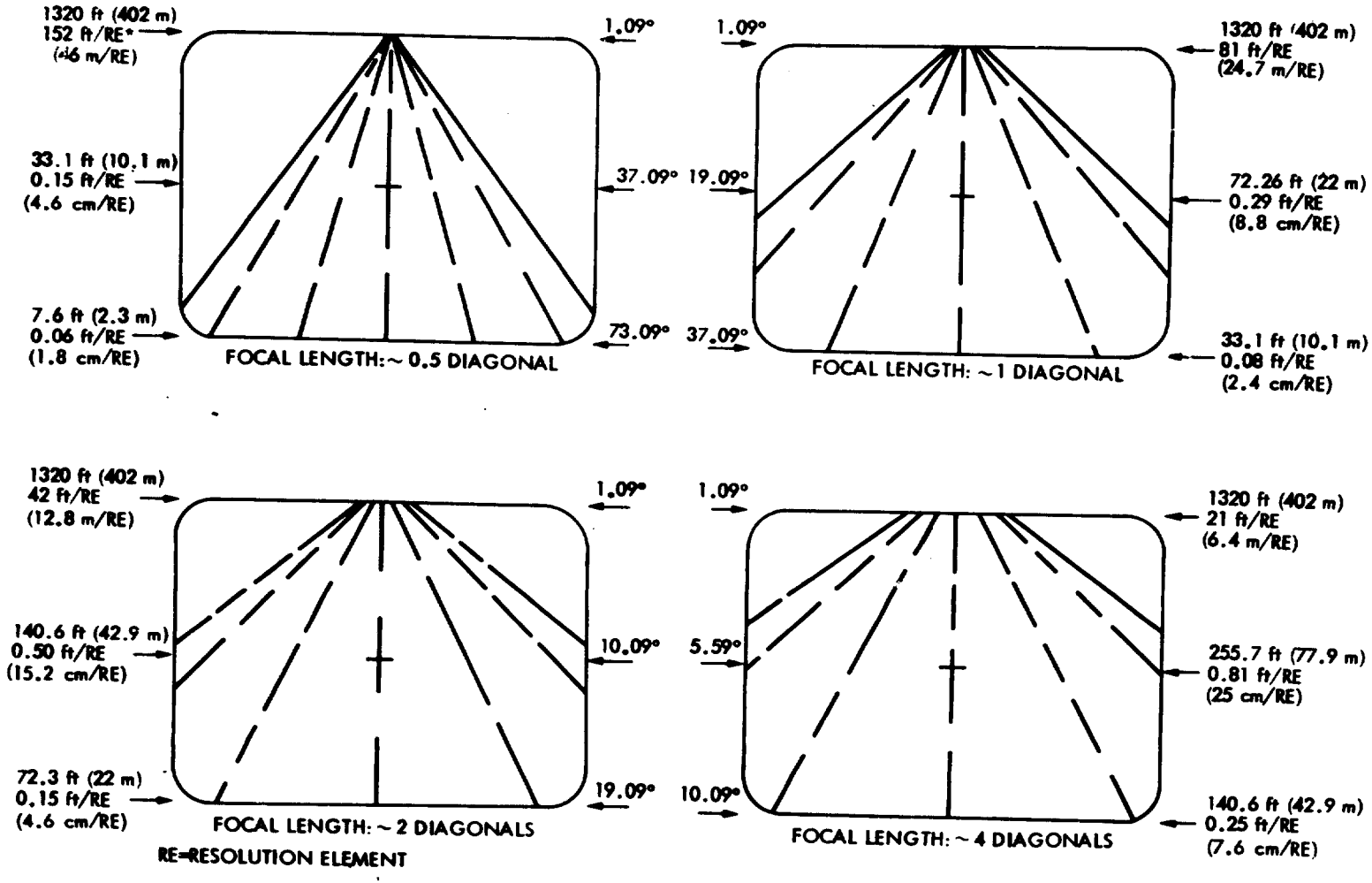

Figure 3-2. TV View From 25 Ft (7.6 M) Height

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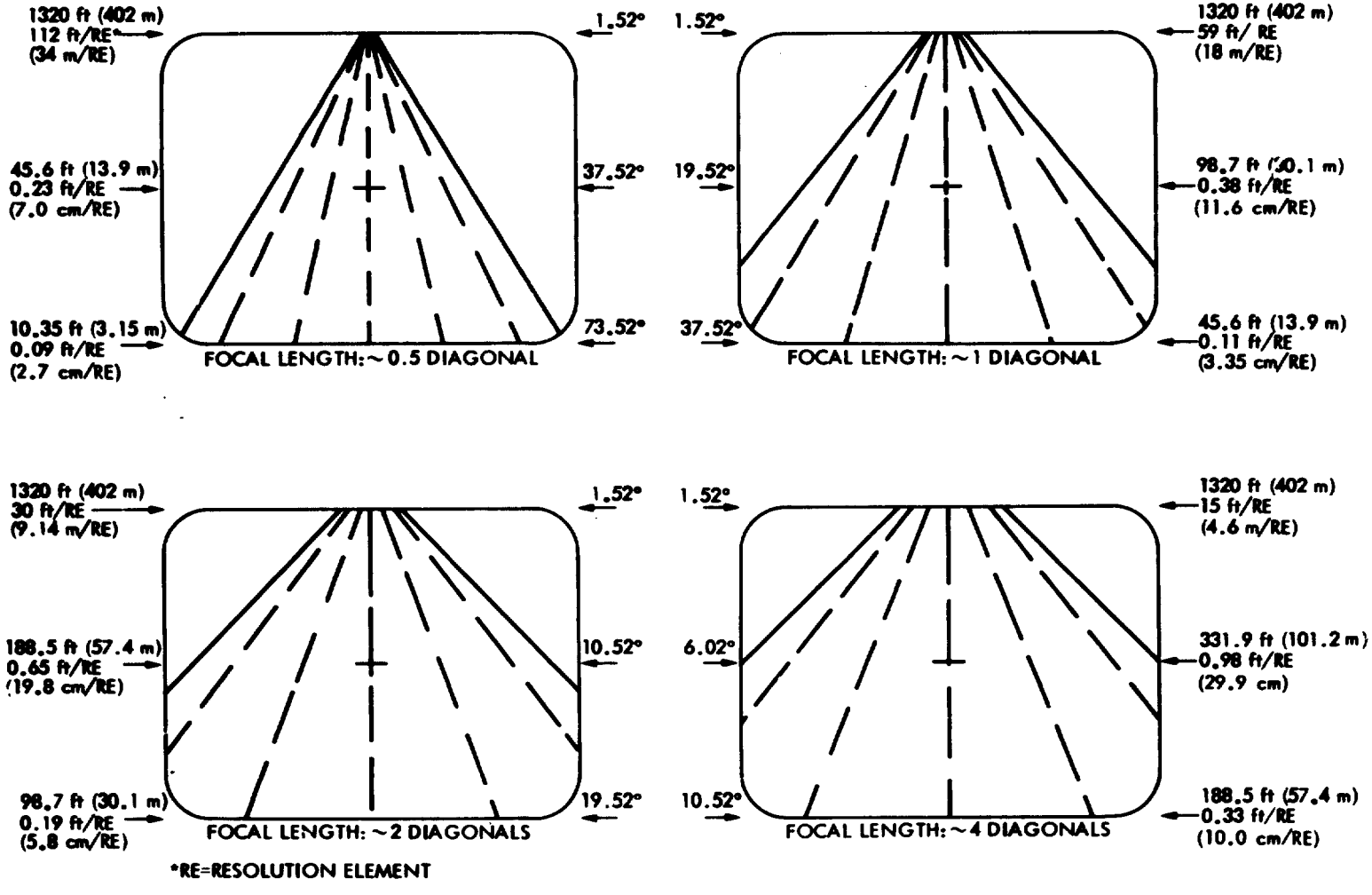

Figure 3-3. TV View From 35 Ft (10.7 M) Height

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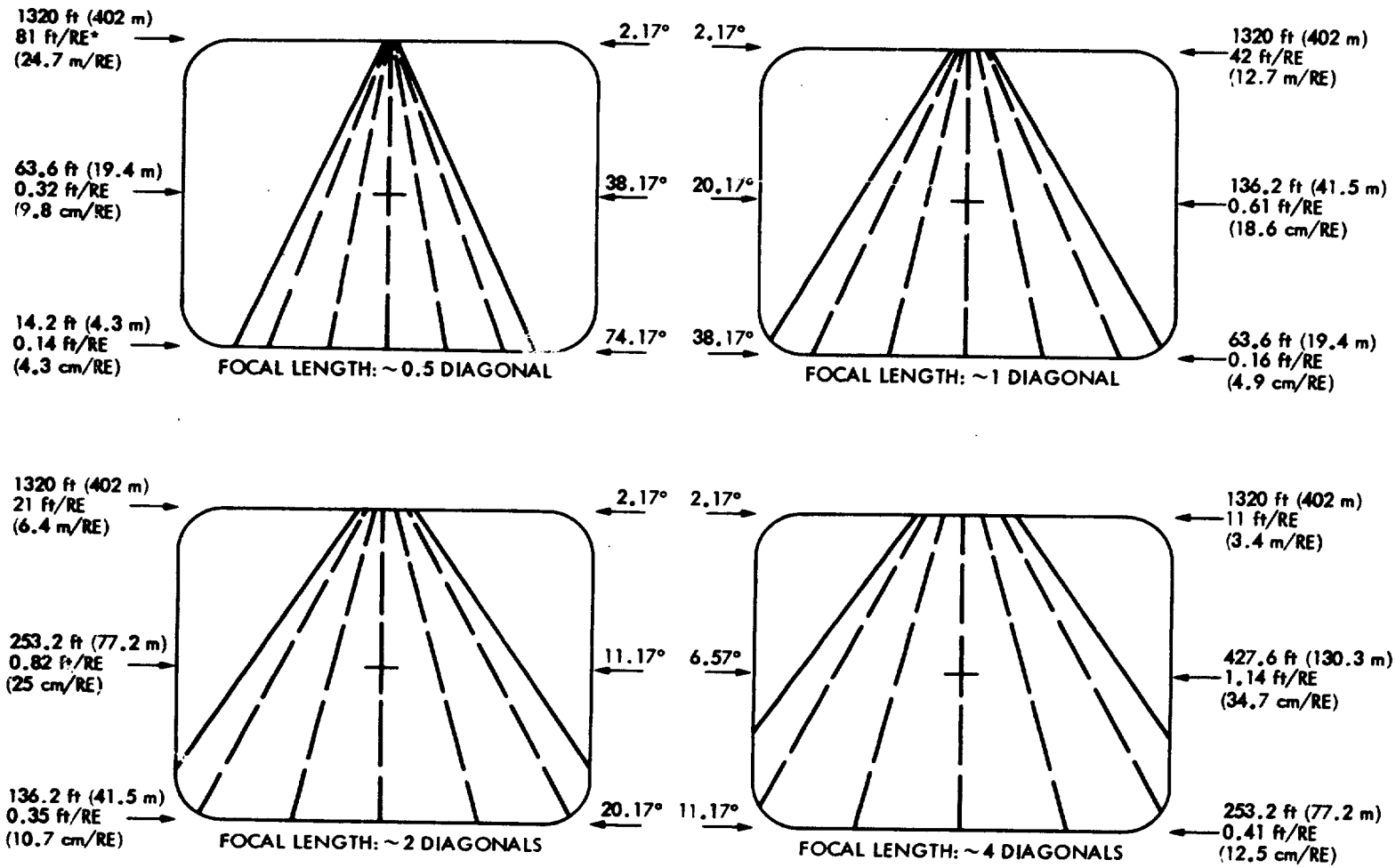

*RE = RESOLUTION ELEMENT

Figure 3-4. TV View From 50 Ft (15.2 M) Height

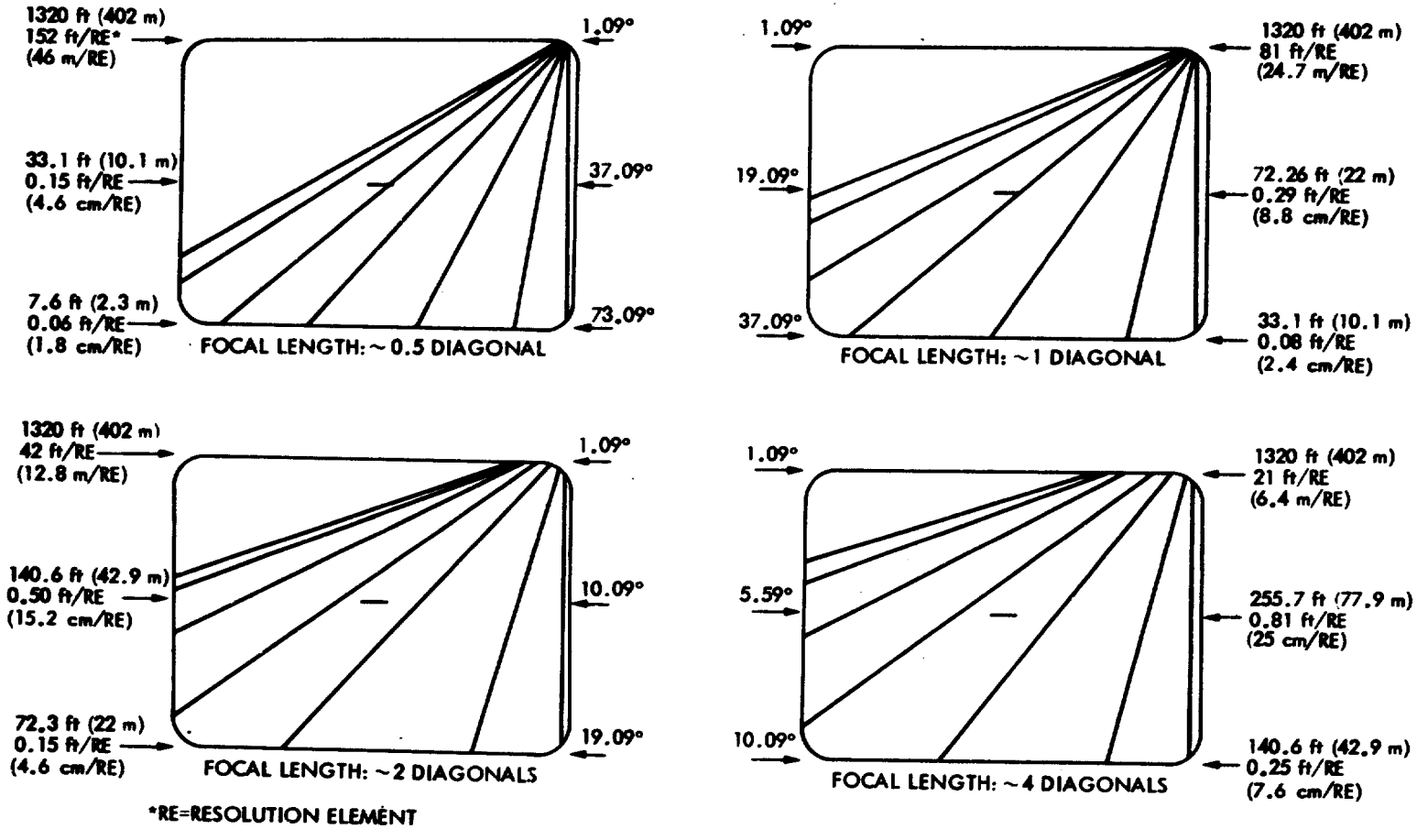

Figure 3-5. TV View From 25 Ft (7.6 M) Height at Roadside

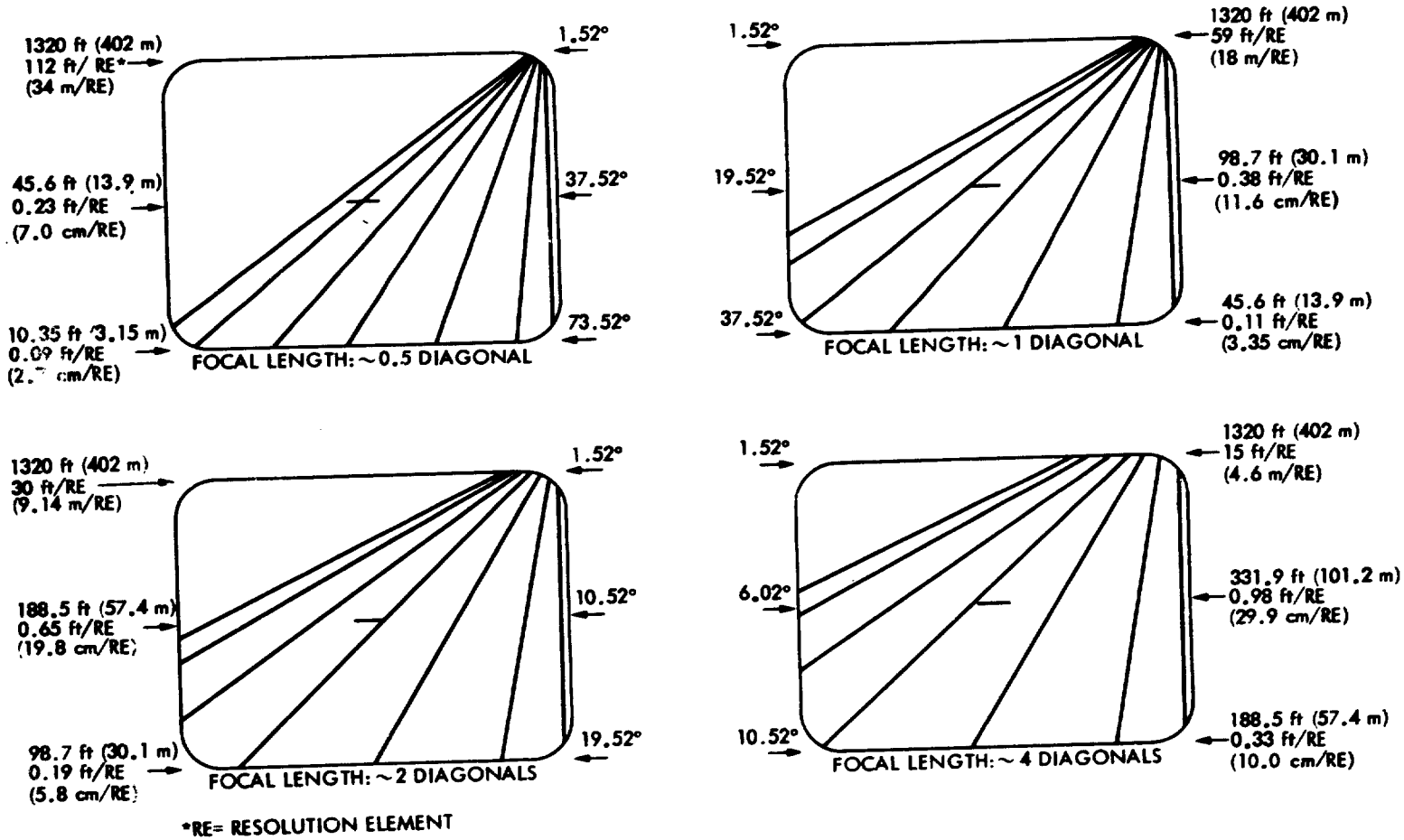

Figure 3-6. TV View From 35 Ft (10.7 M) Height at Roadside

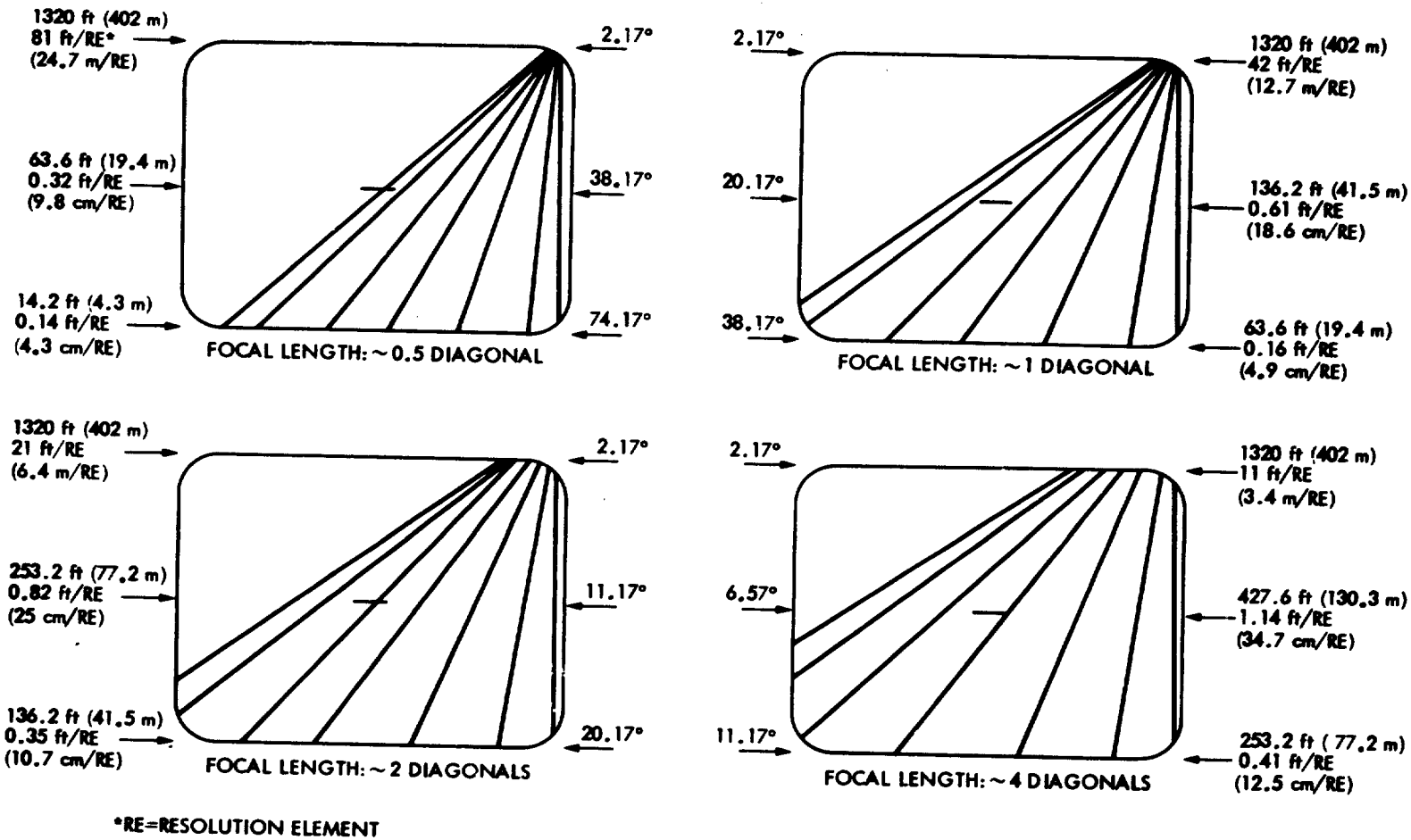

Figure 3-7. TV View From 50 Ft (15.2 M) Height at Roadside

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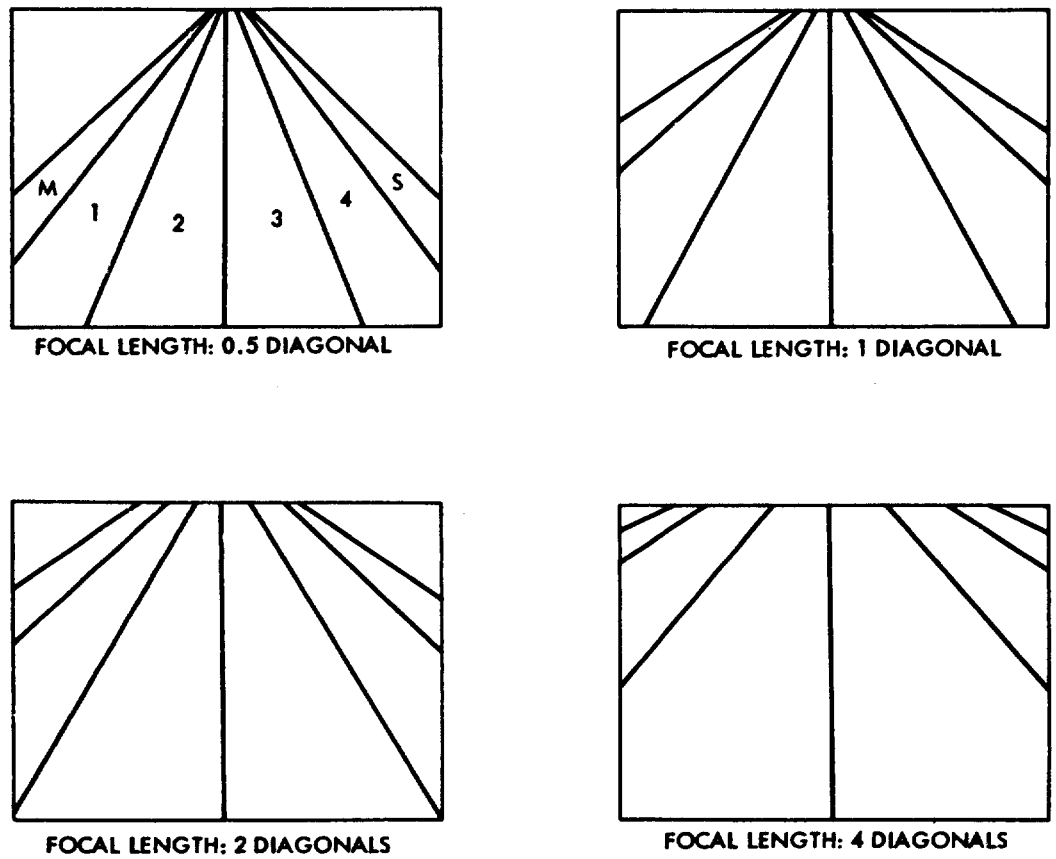


Figure 3-8. Lane-Centered View - 500 Ft (152.4 M) Maximum Range Views from Height of 25 Ft (7.6 M)

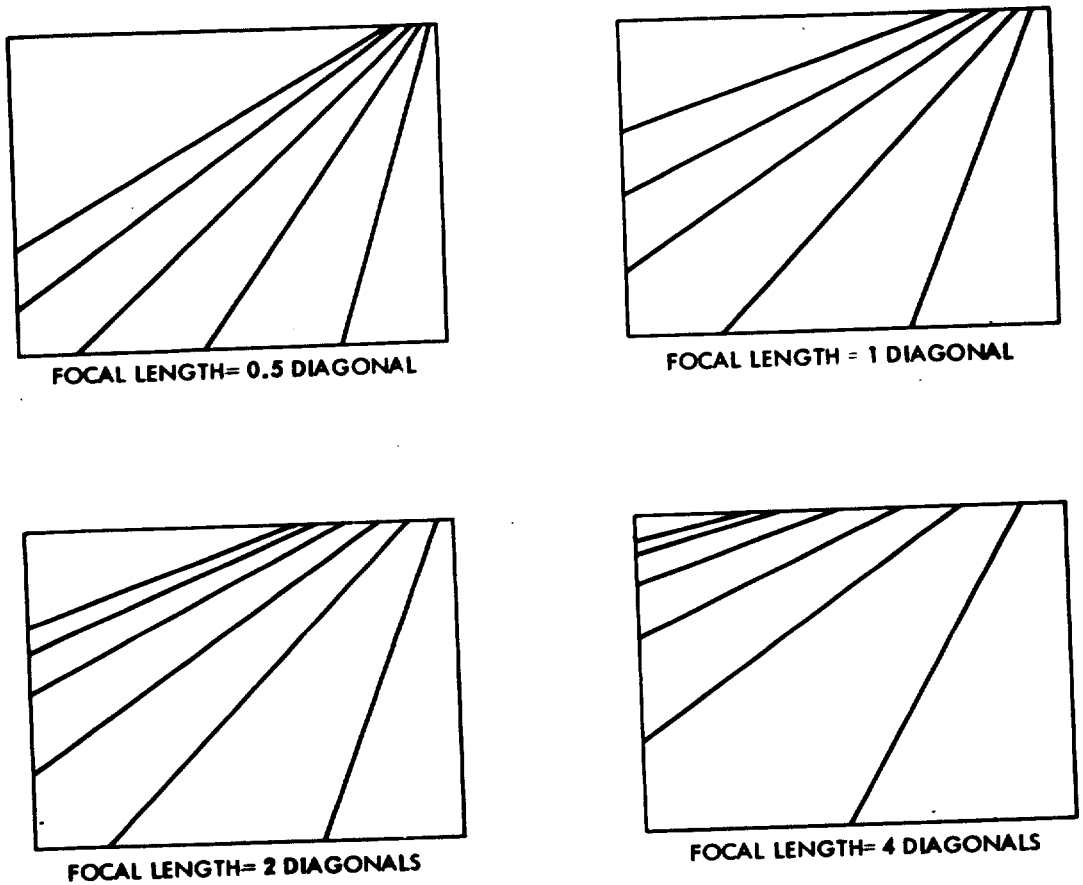


Figure 3-9. Roadside View - 500 Ft (152.4 M) Maximum Range Views From Height of 25 Ft (7.6 M)

Figures 3-10 and 3-11 represent roadside views from a height of 100 feet (30.5 meters). In Figure 3-10 the maximum range is 1320 feet (0.4 kilometer) and in Figure 3-11, 500 feet (152.4 meters). In these views both sides of the freeway can be observed. The nearest distance where all lanes and shoulders are observable is somewhat less than 129 feet (39.3 meters).

From these views it can be seen that the roadway appears extremely narrow at maximum range with normal lenses--some 3° wide. It is apparent that resolving individual vehicles at this range would depend on good, clear viewing conditions at the maximum magnification shown. With a stable mounting and longer focal length, vehicles should be readily discernible.

On the other hand, all four lanes close to the sensor can only be observed by using a lens having a focal length of 1 diagonal or shorter. With this focal length, objects at maximum range appear to be hardly more than a "point". Therefore, one would conclude that a fixed position wide angle or normal lens is required to see all lanes close up for traffic measurement, but would be unsatisfactory for imaging of vehicles at the maximum range. These differing requirements indicate that a variable-focal-length lens and some means of pointing the sensor in the proper direction when using long focal lengths are required.

The views from heights greater than 25 feet (7.6 meters) show that more roadway can be seen and at a closer distance to the sensor with the same focal length lenses. But these views also illustrate the need for variable focal length and pointing to satisfactorily accomplish both tasks.

Resolution

The roadway horizontal intercept angle is about 3° at 1/4 mile (0.4 kilometer) and is 1/4th to 1/32nd of the horizontal scan width at that range. Since horizontal resolution is about a half of the vertical in broadcast-quality TV systems, the roadway at maximum range can be resolved horizontally to about 1.2 to 9 feet (0.366 to 2.75 meters), depending on the focal length employed.

The distance along the roadway subtended by a vertical angle at the WADS sensor can be expressed as the difference between the tangents of the two rays. The distance increases as the reciprocal of the cosine squared. The geometry and formulations are shown in Figure 3-12. As the aiming ray of the view angle is brought near to the horizontal, the distance subtended by a very small angle becomes very large, even when the angle is as small as that between adjacent TV lines. The vertical angle subtended by TV line pairs depends upon the normalized lens/sensor size combination.

Figure 3-13 is a graphical presentation of the distance subtended by a TV line pair as a function of the elevation angle for a sensor height of 25 feet (7.6 meters). The two lenses are a moderately strong telephoto lens (focal length = 4 diagonals) and a very wide angle lens (focal length = 0.5 diagonal) and represent probable extremes encountered

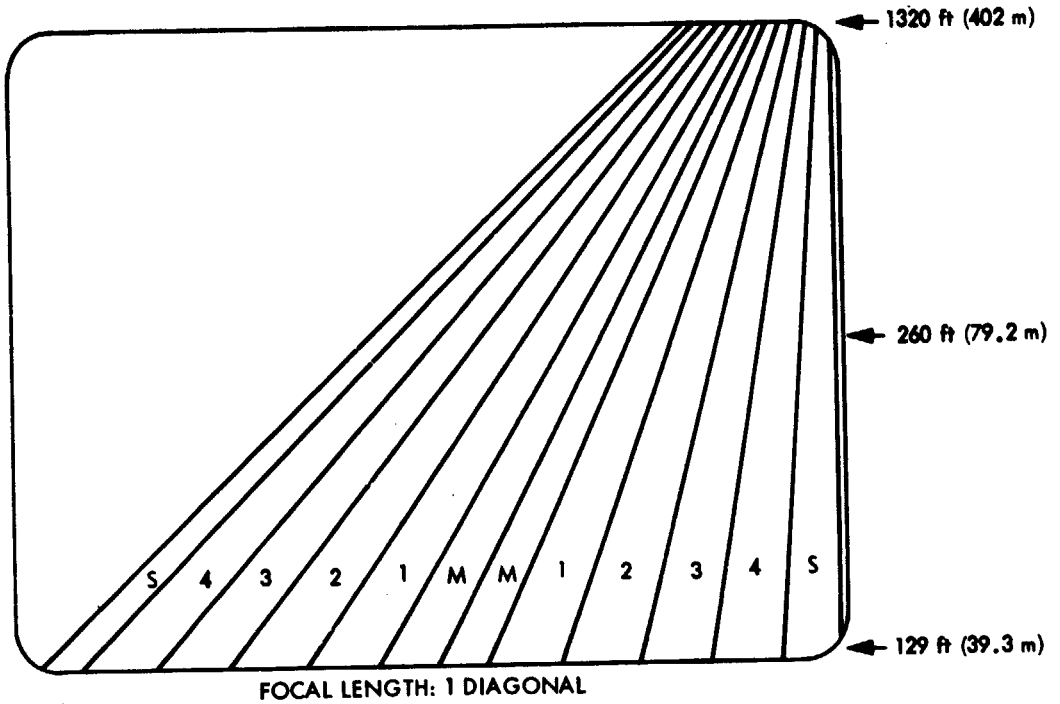


Figure 3-10. Roadside View From Height of 100 Ft (30.5 M). Lanes, 14 Ft (4.28 M); Medians and Shoulders, 10 Ft (3.05 M).

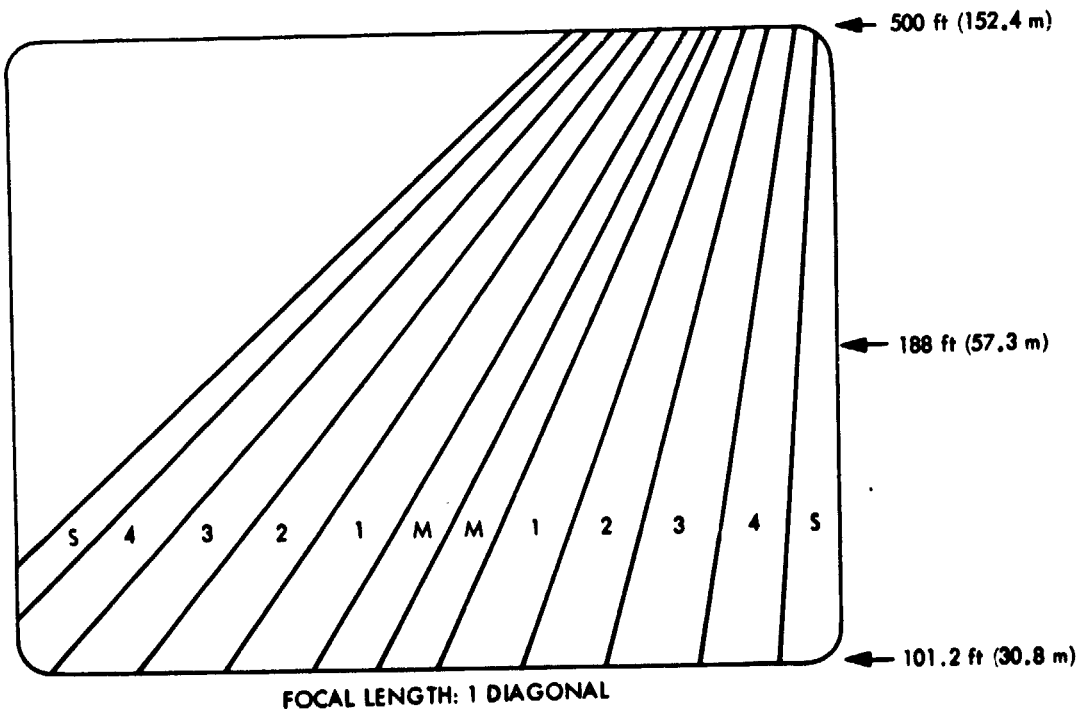
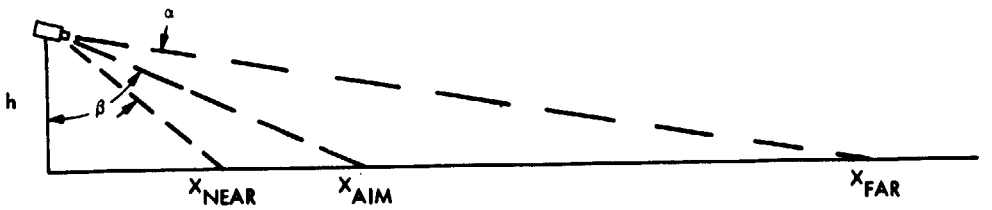


Figure 3-11. Roadside View From Height of 100 Ft (30.5 M)



$$\beta = \mathrm{TAN}^{-1}\left(\frac{X_{AIM}}{h}\right)$$

$$X_{FAR} = h \cdot \mathrm{TAN}\left(\beta + \frac{\alpha}{2}\right)$$

$$X_{NEAR} = h \cdot \mathrm{TAN}\left(\beta - \frac{\alpha}{2}\right)$$

Figure 3-12. TV Resolution

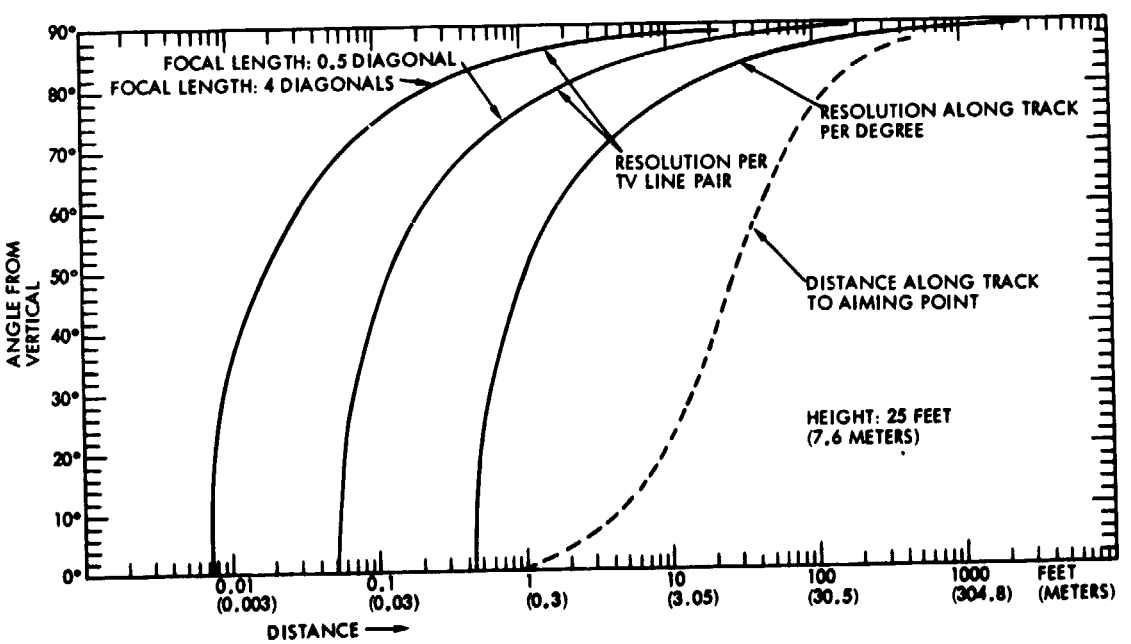


Figure 3-13. Resolution per TV Line Pair

in zoom lenses. The aiming distance (dashed curve) is presented to relate the angle to the distance along the roadway. The graph can be used to determine the elevation angle or resolution by choosing a distance along the roadway; for example, 100 feet (30.5 meters). At this distance the elevation angle is 76°. The horizontal resolution can be found for the "4 diagonal" lens at the intersection with that curve and is about 0.12 feet (3.6 cm). Similarly, the "0.5 diagonal" lens has 1-foot (30.5-cm) resolution at 100 feet (30.5 meters). The resolutions at 200 feet (61 meters) are 0.5 and 2 feet (15 and 61 cm), respectively.

The principal impacts of slant viewing are the rapid deterioration of ranging ability or distance measurement and the decreased accuracy that would occur in speed determinations made at long distances. This decrease in accuracy of distance or speed, together with the increased obscuring of farther vehicles by nearer vehicles, emphasizes the need to have the traffic parameter test section near the WADS sensor.

Elevation angles, horizontal distance, and line pair resolution are shown in Figures 3-2, 3-3, and 3-4 along the side of each view. The values also apply to the views of Figures 3-5, 3-6, and 3-7 for the same vertical part of the picture--top, middle, and bottom.

For these views, the nearest distance which allows observation of all four lanes varies from about 8 to 255 feet (2.4 to 77.7 meters) for the 25-foot (7.6-meter) sensor height. These values are determined by inspection of the views. This distance cannot be decreased by depressing the sensor even though closer parts of the roadway can be seen.

Of the 24 views shown in Figures 3-2 through 3-7, only the few with short focal lengths appear to be able to offer some view of the opposing lanes. The ability increases with height as is illustrated in Figures 3-10 and 3-11, where the opposing lanes may be observed almost as well as the near lanes.

Viewing Limits

A limitation on the use of imaging for parameter measurements arises from the occulting of far vehicles by those closer to the imaging sensor. Other limitations are those due to downgrades, where the roadway disappears from view, curves, where roadside structures obscure the view, and overpasses which block the view beyond a certain distance.

Downgrade View. The limited mounting height available to the WADS determines that the WADS should be placed close to any transition from level to downgrade roadway. The limiting distance to the transition occurs when the projection of the downgrade roadway intersects the WADS sensor (Figure 3-14). At this point, and farther from the transition, the downgrade roadway disappears from view. If the roadway can still be seen, then individual vehicles in different lanes should be as

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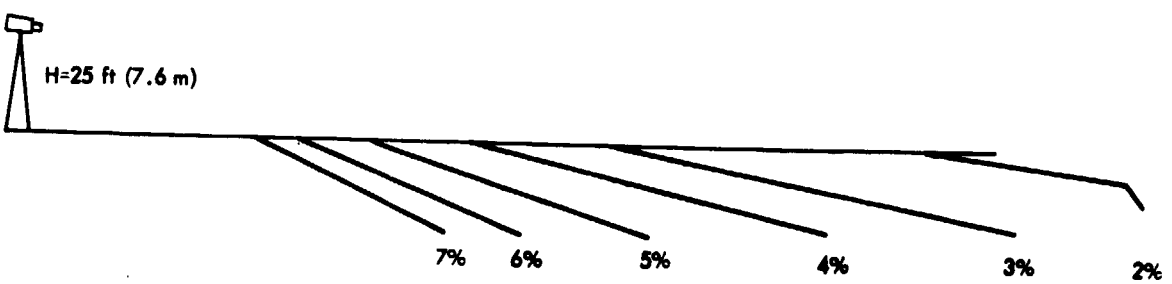
discernible as when the roadway is essentially level. Vehicles in the same lane, especially in the lanes nearest the line of sight, will be harder to separate. Nearer vehicles will completely obscure those directly behind them because the WADS is effectively at road level when looking at the limiting downgrade from a position on a level roadway.

The downgrade portion effectively lowers the apparent height of the WADS only where there is a transition. If there is no transition in grade, then a WADS placed on a downgrade should have the same effective height as if it were on a level roadway.

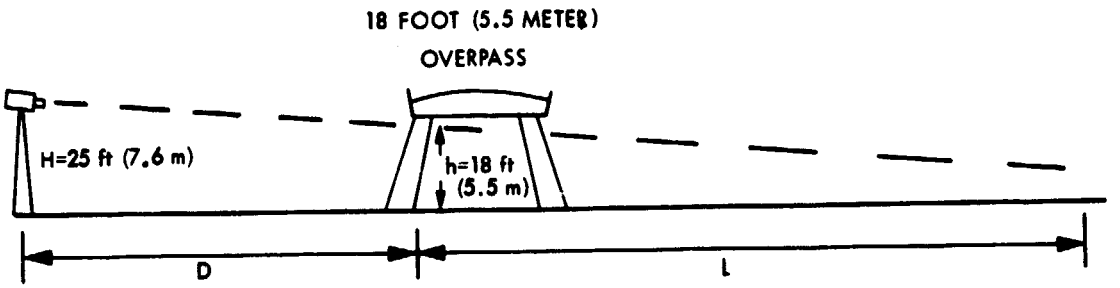
Obstructed On-Grade View. The effect of an overpass over a level roadway is to limit the maximum viewing distance beyond the overpass. The actual range achievable depends on the height of the WADS, the clearance height of the overpass, and the distance from the WADS to the near side of the overpass. The formulation and tabulation of some distance relationships are presented in Figure 3-15. A separation of slightly less than 400 feet (122 meters) between the WADS and an overpass should still allow a total distance of 1/4 mile (0.4 kilometer) to be observed, providing there are no curves or grades.

Curve View. An on-grade curve view geometry is depicted in Figure 3-16. The radii of curvatures of freeways are seldom less than 2000 feet (610 meters) even in metropolitan areas. This number is derived from measurements taken from quadrangle topographic maps in the 7.5 minute series of the Los Angeles area. There are instances of curva-



DISTANCE ALONG TRACK AT WHICH ROAD DISAPPEARS	GRADE (%)	1	2	3	4	5	6	7
	FEET:	2500	1250	833	625	500	417	357
	METERS:	762	381	254	190	152	127	109

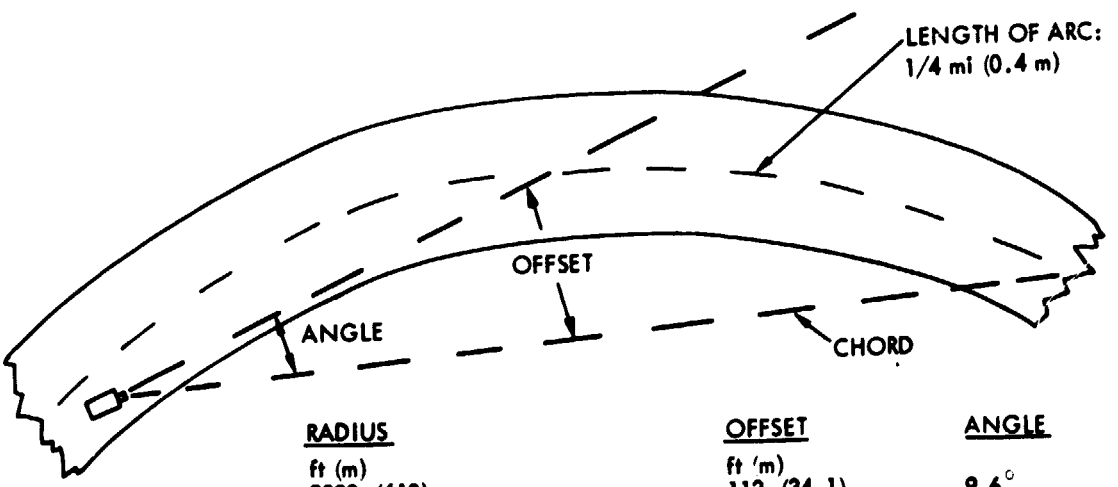
Figure 3-14. Downgrade View



$$\frac{H}{D+L} = \frac{h}{L}$$

D ft (m)	L ft (m)
200 (61)	700 (213)
400 (122)	1000 (305)
800 (244)	2000 (610)
1200 (366)	3000 (914)

Figure 3-15. Obstructed On-Grade View



RADIUS ft (m)	OFFSET ft (m)	ANGLE
2000 (610)	112 (34.1)	9.6°
1320 (402)	176 (53.6)	14.9°

Figure 3-16. Curve View

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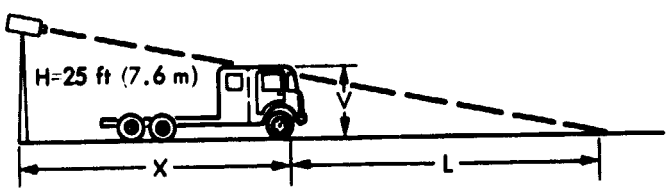
tures as small as 1300 feet (396 meters), but these curves are on freeway sections constructed over 40 years ago. The offset or maximum distance from the chord to the 1/4-mile (0.4-kilometer) arc is a little over 100 feet (30.5 meters). This distance should pose no problem in surface or elevated freeway sections or in depressed freeways with graded or sloping sides.

Depressed freeway sections without ramps and utilizing vertical retaining walls may limit the maximum viewing distance. For example, a four-lane depressed section with overhanging retaining walls has a design right-of-way of 120 feet (36.6 meters) and only 60 feet (18.3 meters) between the tops of the retaining walls. The maximum viewing distance would be determined by an arc-to-chord distance of 30 feet (9.1 meters) which occurs at an arc length of about 700 feet (213 meters) for a 2000-foot (610-meter) radius.

It appears that curved sections where overpasses are in the line of sight will be the most difficult circumstance. The abutments and beams will obscure the view, requiring that each installation be investigated during placement of the WADS so as to obtain the maximum view.

Gaps. The view that the WADS "sees" when looking down the roadway does not allow viewing the roadway shadowed by the vehicle. The roadway is obscured by being in front of the vehicle and therefore hidden from view of the WADS. The amount of roadway obscured increases with distance and vehicle height. Figure 3-17 depicts the geometry of obscuring the roadway based on a 25-foot (7.6-meter) sensor height and



$$L = \frac{V \cdot X}{H - V}$$

X ft (m)	L V=5 ft (1.52 m)	V=10 ft (3.05 m)	V=15 ft (4.57 m)
50 (15.2)	17.5 (5.33)	33 (10.1)	75 (22.9)
100 (30.5)	25 (7.6)	67 (20.4)	150 (45.7)
200 (61)	50 (15.2)	133 (40.5)	300 (91.4)
400 (122)	100 (30.5)	267 (81.4)	600 (183)
800 (244)	200 (60.9)	533 (162)	1200 (366)

Figure 3-17. Gap View

various vehicle heights. The formula shown relates the length, L, of the vehicle "shadow" as a function of vehicle height, V. Several values of V and the distance X from the sensor are presented in the table in Figure 3-17. The same results are presented graphically in Figure 3-18, which shows the occluded distance or shadow as a function of distance from the sensor for three heights of vehicles. Also included are distances representing the vehicle spacings for several densities that indicate the maximum distance from the sensor at which various vehicles cause shadows equivalent to the spacings at these densities.

Conclusions. The 1/4-mile (0.4-kilometer) maximum seeing range for incident investigation can be met from the 25-foot (7.6-meter) sensor height for most freeway geometries if the sensor is equipped with pan and tilt and zoom optics.

The measurement of traffic parameters requires optics with a normal or shorter focal length in order to see four lanes from the 25-foot (7.6-meter) height.

Higher sites for the WADS allow more roadway to be seen; with a 100-foot (30.5-meter) height, both sides of a freeway may be observed.

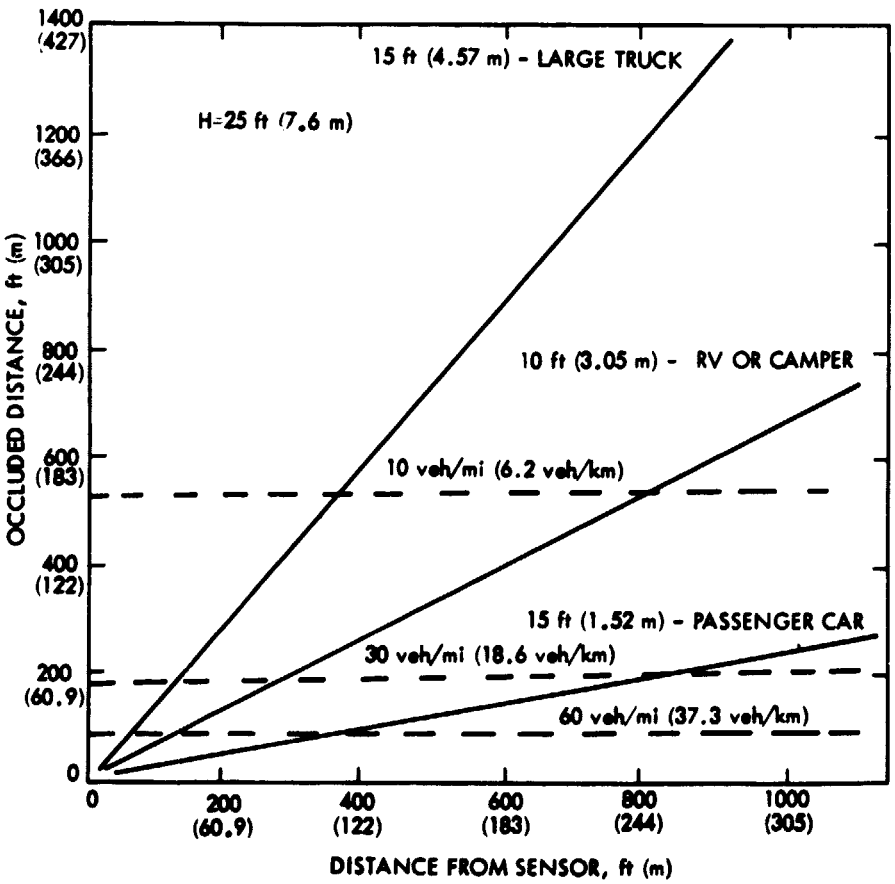


Figure 3-18. Occluded Distance vs. Distance from Sensor

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COMMUNICATIONS STUDY

Communications provides the link for freeway parameter monitoring, selective video freeway incident monitoring, and commanding sensors (cameras) to locate a specific incident.

The communications system should be able to combine low speed, two-way information channels (less than 100 bits per second) with high speed one-way video channels (1-2 megabits per second or 2-4 megahertz bandwidth) into a cost-effective network. The low speed data channels are to be used for continuously monitoring the speed, volume, density, and occupancy traffic parameters from all sensor locations and for transmitting camera commands for locating incidents. The high speed channels are needed for the transmission of real time or near real time video pictures for incident monitoring.

There are many communication system options (e.g., telephone lines, laser, microwave, and coaxial cable). Furthermore, the choice of an optimum communication system will likely depend on the specific location of the application. The choice will be affected by specific characteristics such as the number of sensors, the distance between sensors and their central control station, local ordinances, and local decisions trading-off performance and cost. Therefore, a detailed analysis of the application of all these various communication systems is beyond the scope of this effort. However, in order to provide some insight into the costs associated with the communication system, an investigation was made of the most common communication methods for a specific location in Los Angeles, California.

The methods investigated are listed in Table 3-1. Cost data for 1977 were gathered and evaluated using a 12-mile (19.3-kilometer) long stretch of Los Angeles freeway as a model. Sensors were located at 1/2-mile (0.8-kilometer) intervals along the 12 miles (19.3 kilometers); 3 miles (4.8 kilometers) was used as the distance between the control center and the closest sensor. Costs were based on a 10-year system life. Combinations and variations of investigated methods were studied; however, an optimum system design study was not performed. The cost estimates associated with the various communication options are summarized in Table 3-2.

As Table 3-2 shows, the voice grade (2700 hertz bandwidth) leased or purchased (telephone) lines are low in cost and capable of handling the traffic parameter and camera control data communications, which have low bit rates. These lines can currently carry image data, but only at a rate of one frame per 30 seconds (slow scan imaging), which is much too slow to enable practical remote pan/tilt/zoom operation of the camera for incident verification. It is expected that a minimum frame rate of about one frame per second will be required to enable practical incident verification. Recent advances in the technology of data compression and modems make one frame per several seconds (with 240 x 240 resolution) feasible, but further development is required to realize this capability. When a frame-per-second slow scan imaging capability becomes available, it will offer an important additional communication option for incident verification. The slow scan option will

Table 3-1. Communication Methods Investigated

Leased Telephone Lines
Voice grade (2700 hertz bandwidth - 4800 bits per second)
Conditioned voice grade (<4800 bits per second)
Video
Leased Community Area Television (CATV) Systems
Coaxial Cable Systems
Underground installation
Overhead installation
Microwave Systems
Frequency modulation systems
Multi-channel (amplitude modulation) systems
Two-Way Radio

be significantly lower than real-time TV in initial purchase cost, but of course it will also have a lower frame rate as compared to real-time TV.

Leased community area television (CATV) systems did not encompass all of our sample freeway link. Furthermore, they are designed primarily as distribution systems, and WADS requires a collector system. CATV systems in urban Los Angeles County are restricted to the poor-TV-reception areas. The test freeway section included two CATV companies near some of the sensor locations; other locations had no coverage. Additional cables would be required to interconnect the control center with the 12 sensor locations. Since the CATV systems as presently implemented cannot generally support the WADS concept, costs for this service were not computed.

Microwave systems were limited to one-way video transmission - from sensor to control center. A two-way video system was not required and would need an additional receiver, transmitter, and antenna for each sensor. Microwave costs were further reduced by providing for frequency re-use since three monitors will handle 25-50 sensors, requiring only three receivers.

Installation of the coaxial cables is the primary cost of a cable system. Overhead installations are considerably cheaper than underground, but are not permitted in many urban areas. The digging of trenches through urban regions (for underground installations) incurs substantial risk and environmental impact. Coaxial cables for TV distribution are primarily one directional systems with 20 or more distribution channels

Table 3-2. Communication System Costs

	10-Year Cost for 24 Sensors - 15 Miles (24 Kilometers) ($)	Cost per Sensor for 10 Years ($)
SLOW SPEED		
Leased Lines (Telephone for Low Speed Parametric Data and Camera Commands)		
Full duplex multidrop private line for 24 sensors . . .	30,000	1,250
Full duplex private line for each sensor	144,000	6,000
FM Radio (15 kilohertz bandwidth)		
Two FM transceivers at $250		500
Installation		150
Maintenance		350
		1,000
HIGH SPEED		
Microwave		
Three microwave receivers (with antennas)	36,000	1,500
Transmitter (with antenna)		12,500
Installation	75,000	3,125
Coaxial Cable: 7-channel Forward and Reverse		
Overhead - 15 miles (24.1 kilometers) @ $10,000 per mile ($6214 per kilometer) . .	150,000	6,250
Underground - 15 miles (24.1 kilometers) @ $20,000 per mile ($12,427 per kilometer)	300,000	15,625
50% overhead and 50% underground	225,000	9,375

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from the "head-end" to the customer. WADS requires a two-way cable system with a capacity of four to nine channels in each direction. The coaxial cable system selected was a seven channel forward, seven channel reverse, two-way trunk, because it satisfies the system requirements at the lowest cost. A two-way coaxial cable system will satisfy all system requirements without combination with other methods.

Table 3-2 gives the costs of the methods investigated. A range of costs is provided to cover various possible configuration and installation conditions. Innovative installation methods utilizing permanent freeway median barriers, installation of a cable in conjunction with emergency freeway telephones, and other location-unique methods could drastically impact the cost of a coaxial cable communication system.

PRODUCTION SENSOR COST ANALYSIS

Production costs (Table 3-3) are projected for a 10-year system operating life, based on production of 100 units commencing in 1980. The WADS system consists of three subsystems: sensor or camera; electronics and control; and communications. No costs are included for control room displays, computers, converters, or ancillary equipment. The communications system includes all of the hardware necessary for sending low speed data to and from the control room, but not that for sending video signals to the control room. The cost of video communications was discussed in the previous section.

The system will be purchased, installed, and maintained by or under contract to agencies of municipal, state, or federal government.

The analysis is unitized to the capital cost of one unit in production lots of 100 units. It includes material overhead, subsystem assembly and test, labor overhead, G and A, and profit. System engineering costs for implementing a system for a specific freeway corridor were not included in the estimate. Since plans for the freeway corridor are in existence, engineering costs should be minimal.

Table 3-3. Cost per Unit (to Nearest $5) for WADS Hardware, Based on 100-Unit Production and a 10-Year System Life (1980 Prices)

Video camera with lens	$1,250	
Enclosure (pressurized)	675	
Pan and tilt mechanism	550	
Environmental shield	25	
Pole (25-35 ft)	750	
Material cost	$3,250	
Material overhead (13%)	425	
	$3,675	$3,675
Assembly and test	500	
Labor overhead (86%)	425	
	$ 925	$ 925
Electronic Subsystem		
Microprocessor and memory	$1,400	
Converter - analog to digital	150	
Communications interface	200	
Power supply	200	
Modem	800	
Enclosure with fan	350	
Material cost	3,100	
Material overhead (13%)	405	
	$3,505	$3,505
Assembly and test	$1,000	
Labor overhead (86%)	860	
	$1,860	$1,860
Manufacturing costs (including overhead)		$9,965
G&A (22%)		$2,190
Subtotal		$12,155
Profit (15%)		$1,825
Total Capital Costs - Sensor and Electronics		$13,980
Installation		
Site engineering (per unit)	$ 100	
Sensor	2,000	
Electronics	1,350	$3,450
Total Installed Capital Cost		$17,430

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SECTION IV

IMAGING TECHNOLOGY SURVEY

INTRODUCTION

A wide variety of image sensors exists which could be considered for the WADS application. There are at least a dozen television camera image sensors as well as several types of "thermal" imaging sensors, cameras which are sensitive to the long wavelength radiation emitted by all warm objects. This section of the report discusses all-weather and day/night "seeing" conditions for both visible and IR image sensors, sensor characteristics, and available optics, and recommends a candidate sensor for the WADS application.

The trade-off between visible and long wavelength imaging sensors is considered in some detail. Visible imaging sensors have obvious advantages of low cost and ready availability resulting from their high volume production. Infrared image sensors, although currently very costly, have the advantage of a simpler and less variable image, relatively independent of lighting conditions and uncluttered by shadows.

VISION THROUGH THE ATMOSPHERE

The requirement for all-weather vision is central to the WADS concept. It is essential that sunlight, darkness, rain, snow, or fog do not interfere with the traffic data-gathering function. Vision, as usually defined, is an anthropomorphic function. The term is used here in a broader sense to include electronic vision not limited to the human spectral response region.

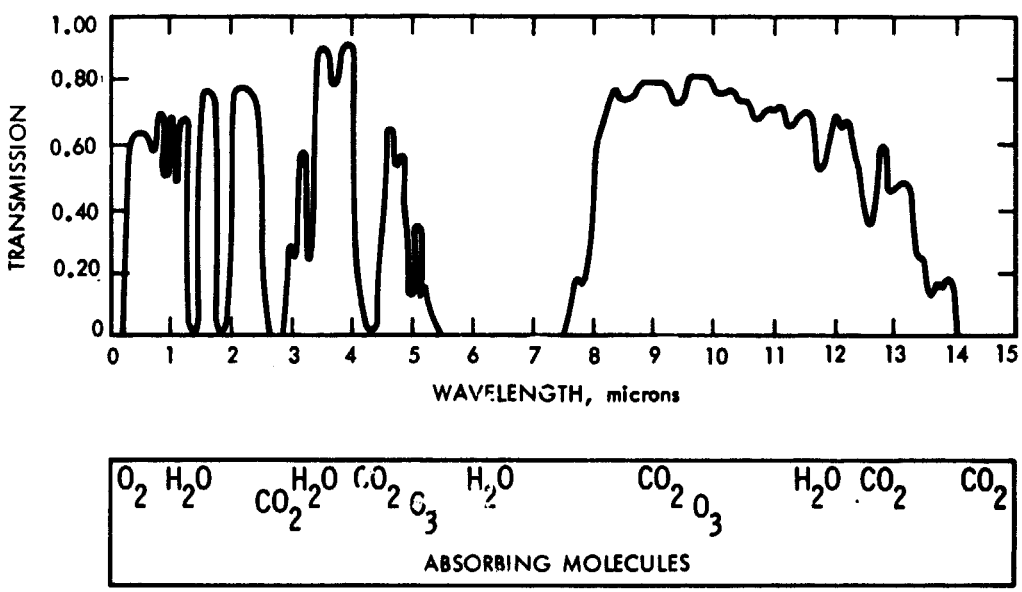
Vision is a function involving many parameters, including ambient irradiation and spectral distribution, spectral and angular reflectivity of the target, spectral reflectivity of the surround, angular subtense of the target, contrast transfer function of the optics, contrast transfer function of the detector, spectral absorption and scattering characteristics of the atmosphere between the image sensor and the target, spectral response of the sensor, and spectral emittance of the target.

In order to discuss the subject, we make a number of simplifying assumptions and consider some limiting cases. We assume the target angular subtense to be a large enough proportion of the imaged field that contrast transfer functions of the optics and the image sensor are close to unity and may be neglected. We require that any sensor to be considered have adequate sensitivity to provide high quality video of traffic under all illumination conditions. In the case of the visible light cameras, this means that the camera should be able to image by ambient light down to that illumination level at which essentially all vehicles have turned on their headlights. In the case of the infrared cameras, this requires adequate sensitivity to distinguish vehicles based on temperature differences relative to the background temperature. These differences may vary widely with the time of day and the time of year.

We shall begin by looking at weather-related processes in the atmosphere which affect image contrast. Transmission through the atmosphere is limited by absorption and scattering processes which obey the relationship

$$T = e^{-[\alpha(\lambda) + \gamma(\lambda)]\, x}$$

where α is the absorption coefficient, γ is the scattering coefficient, and x is distance along the direction of propagation. Both α and γ may be functions of wavelength. Atmospheric absorption is primarily due to molecular components, although scattering agents may exhibit some absorption as well. Figure 4-1 shows the spectral transmission of a horizontal path 6000 feet (1829 meters) in length at sea level for a nominal day (Ref. 4-1). The temperature is 68°F (20°C) and the humidity is 60%, corresponding to 17 mm of precipitable water along the line of sight. The molecular species principally responsible for strong local absorptions is identified at the bottom of the figure. Transmission within the visible region and near-infrared is shown to be about 65% and is principally limited by water vapor; a very low humidity would result in an essentially unity transmission within this band. Note the broad transmission window stretching from 8 to 13 microns. This important window transmits the bulk of thermal radiation emitted by warm bodies. We note that the transmittance within this window is also principally limited by weak, broadband water vapor absorption.



FOR 6000 ft (1829 m) HORIZONTAL PATH, SEA LEVEL, CONTAINING 17 mm PRECIPITABLE WATER. CORRESPONDS TO 60% HUMIDITY AT 68°F (20°C).

Figure 4-1. Typical Atmospheric Transmission

Figure 4-2 plots the visible light transmission of air under very nearly worst case conditions: 100% relative humidity at a temperature of 95°F (35°C), and containing approximately 64 mm of precipitable water per mile (adapted from Ref. 4-2). Note that transmission is about 70% for a pathlength of 1/2 mile (0.8 kilometer), the maximum viewing distance required of the WADS image sensor. Transmission within the 8 to 13 micron region is similarly unaffected for a 1/2-mile pathlength by conditions of "worst case" humidity.

Atmospheric scattering is caused by particulate matter in suspension, in addition to a low level of scattering by the air molecules themselves. Typical scattering sources are salt crystals, fog droplets, smog droplets, dust, smoke particles, rain, and snow. Scattering is a process which is sensitive to the relative dimension of the scattering particle and the wavelength of the scattered radiation. The scattering coefficient is of the form

$$a = \frac{\pi}{2} \sum n(r) \quad K(r/\lambda) \; r^2$$

where n(r) is the population density of particles having a radius of r, and K is a scattering efficiency variable dependent on the ratio of the particle radius to the wavelength of the incident radiation. Figure 4-3 plots K against r/λ (Ref. 4-3). This plot shows that scattering of large particles is proportional to their cross-sectional area, that scattering is enhanced at $r/\lambda = 1$, and that area-scattering efficiency falls toward zero as r/λ approaches zero. For particles small compared with the wavelength of light, the scattering coefficient varies with λ^{-4}, the so-called Rayleigh scattering. Direct visual experience can

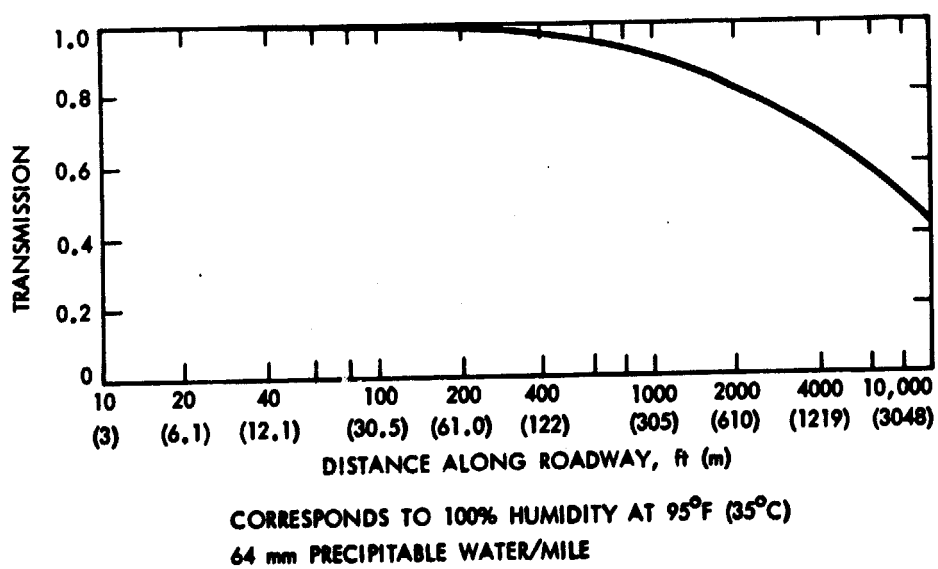


Figure 4-2. "Worst Case" Atmospheric Absorption Visible Light

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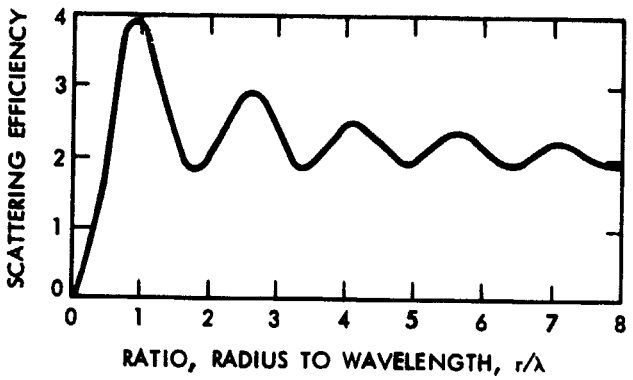

Figure 4-3. Scattering Efficiency Dependence on Wavelength

be correlated with this description: the blue color of air and tobacco smoke and the white color of clouds, as seen by scattered light, are a result of the particle-size distributions. Cigarette smoke particles and air molecules are smaller in size than visible wavelengths, and so preferentially scatter the shorter wavelengths present in visible light. Cloud droplets are comparatively large so that the scattering coefficient is constant with wavelength across the visible spectrum.

The principal scatterers with which we are concerned in this report have particle distributions which are peaked at dimensions large compared with visible wavelengths. Snowflakes and rain drops are typically 250 microns or larger in diameter. Fog droplet distributions vary considerably with locality, humidity and time, but the peak is typically located between 1 and 15 microns. However, haze and smog, which are much less concentrated, often have distribution peaks at or below 0.5 micron. We can conclude that an imager sensitive to infrared radiation in the 10-micron region would always have improved "visibility" over a visible light imager for seeing through smog and haze, sometimes for fog, and not at all for rain and snow.

Absorbing processes do not change scene contrast; they only reduce the effective scene illumination. However, scattering processes can significantly reduce contrast, and so degrade the usefulness of an image. The probability of radiation being scattered out of the line of sight from a target is approximately equal to the probability of radiation from the mean surround being scattered into the line of sight.

$$B_T \approx B_{OT}\, T + \overline{B}_S\, (1-T) \quad \text{(Ref. 4-4)}$$

$$B_S \approx B_{OS}\, T + \overline{B}_S\, (1-T), \text{ so}$$

$$C = \frac{B_T - B_S}{2(B_T + B_S)} \approx \frac{(B_{OT} - B_{OS})T}{2(B_{OT} + B_{OS})\, T + 4\, \overline{B}_S\, (1-T)}$$

where

B_T = observed brightness of the target

B_S = observed brightness of the adjacent surround

$\overline{B}_S$ = mean brightness of the wide angle surround

B_{OT} = brightness of target in the absence of scattering

B_{OS} = brightness of the adjacent surround in the absence of scattering

C = contrast of the image against adjacent surround.

Note that contrast approaches zero as the scattering proportion (1-T) approaches unity.

It is common experience that drivers turn their lights on under conditions of reduced visibility, and a very large scattering ratio is required to render headlights or taillights not visible. We must, however, expect degraded viewing for lesser conditions.

Figure 4-4 plots visible light transmission vs distance along the roadway for a range of fog and haze conditions found described in the literature (adapted from Ref. 4-5). The distinction between fog and haze is somewhat arbitrary. Haze particles may serve as condensation nuclei, and after the droplets have grown to about 1 micron or greater in diameter, the term fog is applied. The densest fog that we have found described has an attenuation coefficient in the visible region of 40/km and is plotted in Figure 4-4 as a limiting case. The boundary between haze and fog has, again, been somewhat arbitrarily defined as occurring at an attenuation of 4/km.

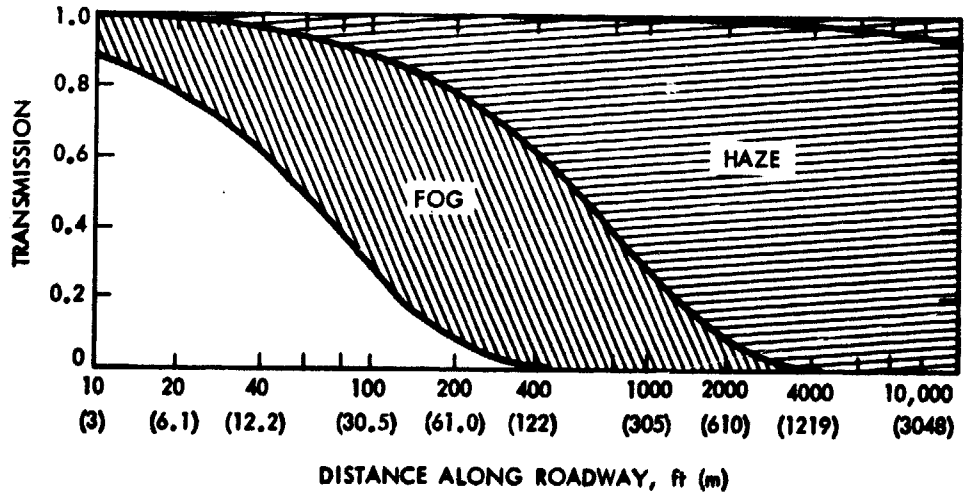

Figure 4-4. Transmittance Through Haze and Fog - Visible Light

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This plot shows that even haze will sometimes interfere significantly with the 1/2-mile (0.4 kilometer) traffic-monitoring function, but that even the worst of fogs should not interfere significantly with the traffic data-gathering function, assuming the data is gathered within 200 feet (61 meters) of the station and that vehicles have their lights turned on during the heavier fog conditions.

Similarly, Figure 4-5 illustrates visible light transmission for nearly "worst case" rainfall and typical heavy snowfall conditions (Ref. 4-6). Both interfere with long-distance visibility, but do not significantly degrade a close-up data-taking function. It is possible that blowing-snow conditions may be more adverse than is represented in Figure 4-5; no information has been found for this condition.

The data presented in these two figures may appear to be contrary to experience; we have all driven in fogs or storms "so bad you can't see across the road." The reason is that we are looking out through a region which is very intensely illuminated by the automobile headlights. Backscatter is quite bright, and so the landscape contrast is very heavily degraded. The WADS sensor, in equivalently bad weather, will be looking along a largely unilluminated path at automotive lights. Backscatter here is small, so does little to degrade the image.

Since one of the reasons for interest in using the thermal infrared (8-13μ) band for a WADS imager is the possibility of fog or smoke penetration, it is useful to compare IR and visible light visibility under the same conditions. It is also of interest to estimate the decrease in the outage probability that an IR system might bring. A rationale for doing so is suggested in the following paragraphs.

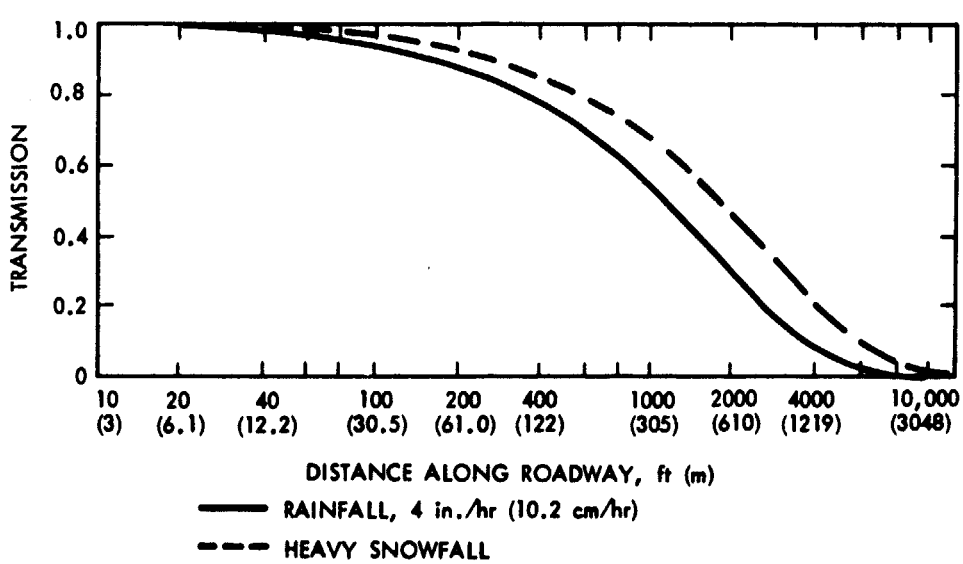

Figure 4-5. Transmittance Through Rain and Snow - Visible Light

Figure 4-6 is a statistical plot of weather data in a form useful for our purposes. The abscissa is the value of visibility (meteorological visibility, defined as the maximum distance at which a large object can be seen). Visibility has a subjective meaning in this sense, but it can be made quantitative. For example, a common definition is the distance at which image contrast is reduced to 0.02 of its original value. A special definition is needed in cases where human vision is not involved, as in the WADS function. The meaning of the parameter V would in this case become the distance at which the imaging device ceased to perform its intended function. The ordinate in Figure 4-6 is the probability that the visibility is worse than the specified value V.

The curve shown in Figure 4-6 is from actual data taken at Hanover, Germany, for the month of January (Ref. 4-7). This data is representative of a rather foggy site. The data, of course, apply to a specific location and season, and will vary for sites in different parts of the country, or even for different locations in the same city.

Note that, as plotted, the curve in Figure 4-6 can be directly interpreted as an outage probability. Since we have assumed that the sensor ceases to function at a distance equal to V, if the abscissa is interpreted as WADS sensor viewing distance, the ordinate becomes the probability of a functional outage of the WADS system as a function of viewing distance.

So far, we have been implicitly considering visible light, or conventional visible-light TV cameras. In order to compare the

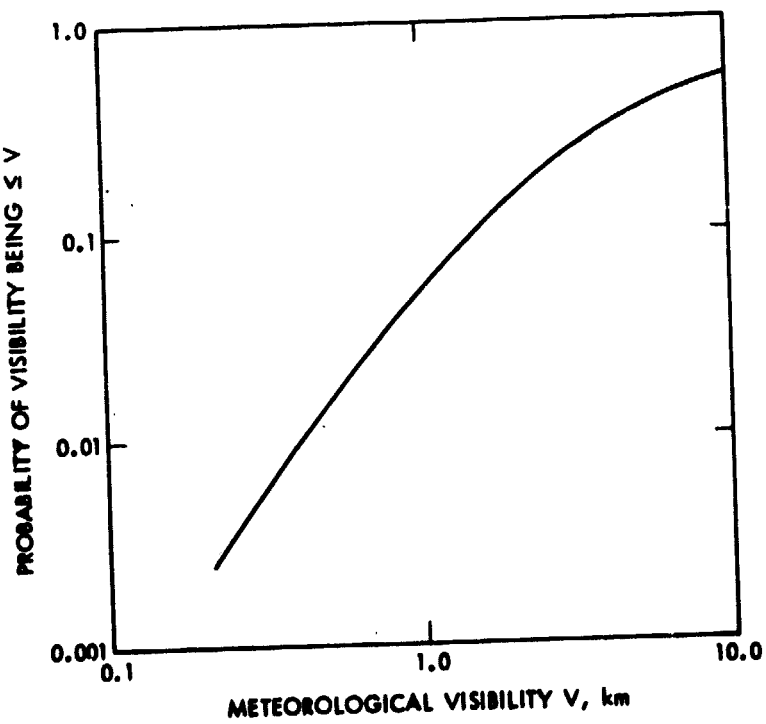

Figure 4-6. A Plot Showing Probability of Reduced Visibility at Given Site

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performance of a visible-light system to an IR system, consider Figure 4-7. In this graph are plotted (qualitatively) the relative visibility for an IR imager in terms of the visibility experienced under the same conditions by a visible-light system. The data points shown are for one particular set of measurements reported in the unclassified literature (Ref. 4-8). Note that in smoke and haze, an IR system may "see" as much as 10 times as far as a visible-light system, whereas in dense fog (V < 1 km), an improvement of a factor of two or three is the best that could be hoped for. An important point is that the improvement factor is variable, depending on conditions and, depending on location, wet vs dry fog, smoke or snow.

Figure 4-8 is a replot of Figure 4-6 in which the corresponding IR visibility curve has been added, based on an assumption that the data points in Figure 4-7 for fog correctly describe the improvement in IR visibility. This assumption is unjustified, and may be optimistic, but it illustrates the computational process necessary to estimate the benefit of IR due to improved visibility range. The two curves are for visible light and IR imagers, and are interpreted as indicating outage probability vs sensor viewing distance for each type of sensor. The benefit is seen to be a reduction in the weather-related outage probability by a factor of approximately three for this hypothetical example.

Although, as noted, rain does not interfere very significantly with traffic data acquisition from the standpoint of visibility, reflectance of the wet roadway will provide a cluttered image field to the

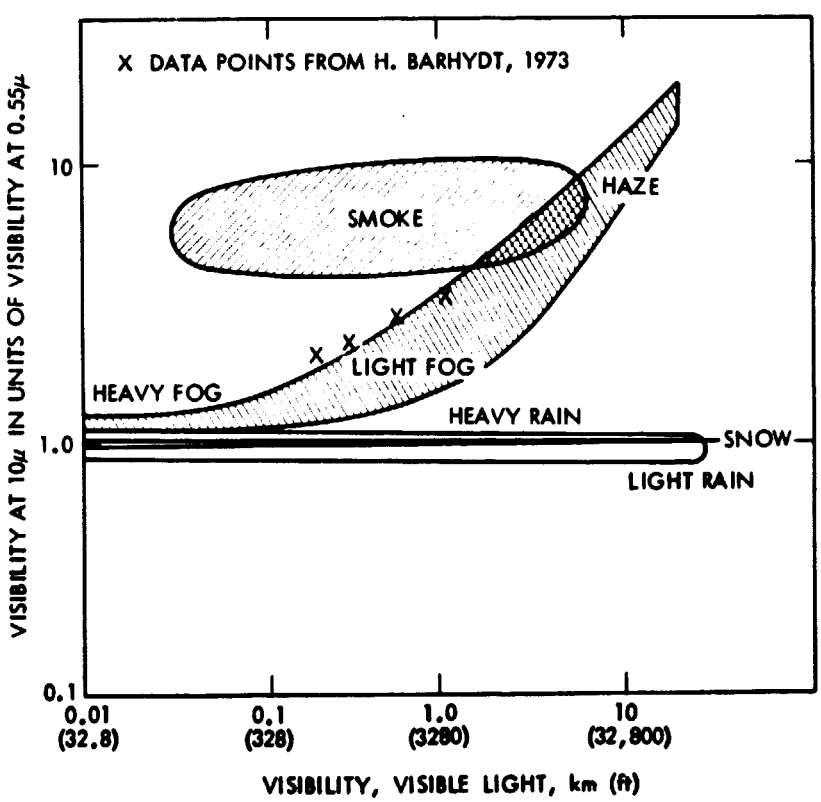

Figure 4-7. IR Visibility Data

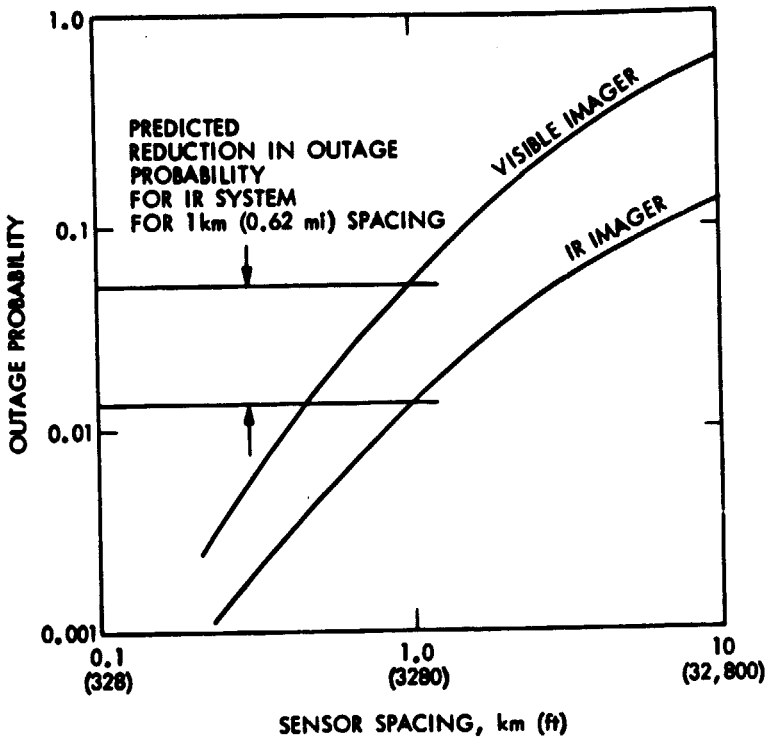

Figure 4-8. Outage Probability for IR and Visible-Light System, Assuming Data in Figures 4-6 and 4-7 Apply

WADS sensor. Highlights are reflected at low angle so that the sensor sees an extra set of headlights per vehicle (if the wet surface is smooth) or sees a generally bright roadway if the surface is very disturbed, as in a very heavy rain. We can calculate the smooth reflectance of the wet roadway,

$$R = \left[\frac{\sin^2(\phi - \phi')}{\sin^2(\phi + \phi')} + \frac{\mathrm{Tan}^2\,(\phi - \phi^1)}{\mathrm{Tan}^2\,(\phi + \phi^1)}\right]$$

where

ϕ = incidence angle of light upon wet surface

ϕ' = incidence angle of refracted light within the water film, $\phi' = \sin^{-1}\left(\frac{\sin\phi}{n}\right)$

n = index of refraction of water = 1.33 for visible-light wavelengths

Figure 4-9 plots the smooth, wet-film reflectance as a function of distance from the camera station for visible light. The camera is assumed to be mounted 25 feet (7.6 meters) above the roadway. Notice that at

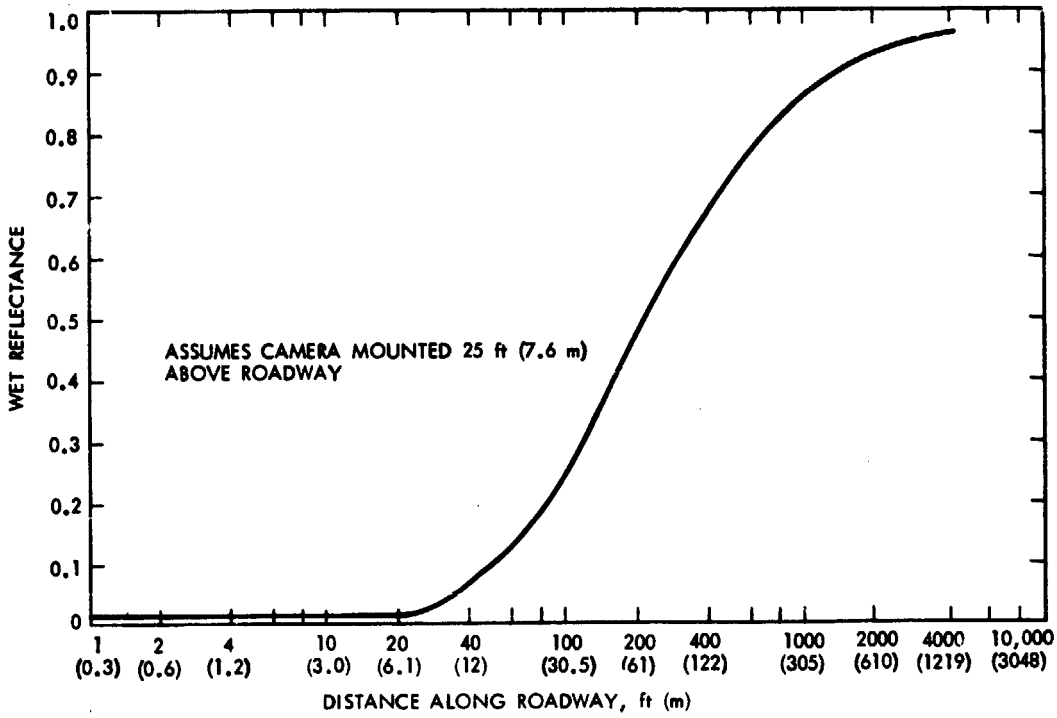

Figure 4-9. Wet Roadway Reflectance - Visible Light

distances of 1/2 mile (0.8 kilometer) or greater, headlights and their reflections may be indistinguishable on the basis of brightness. At a distance of 200 feet (61 meters) or less, the headlights are brighter than the reflection by a ratio exceeding 2/1. If the film surface is at all disturbed, the ratio will be very much greater. Under conditions of thermal IR viewing, qualitatively similar effects would be seen.

It appears that the WADS sensor detection algorithm must have an adaptive discrimination capability to avoid generating incorrect traffic data during rainy weather. An additional discriminant could be the separation between the vehicle and its reflected image (see, for example, Figure 4-10). At distances or 200 feet (61 meters) or less, the along-the-road separation of headlights and reflection is 40 feet (12.2 meters) or less, for headlights at 30 inches (76 cm) and WADS at 25 feet (7.6 meters) above the roadway.

Scene dynamic range is another variable that requires adaptation on the part of the WADS sensor. All image sensors have limited dynamic ranges over which the video signal remains nearly proportional to a power of the optical signal,

$$S_{video} \sim (S_{optical})^{\beta}$$

above the below the range for constant β, transfer curve approaches constant values. Dynamic ranges of up to 10^4 are available.

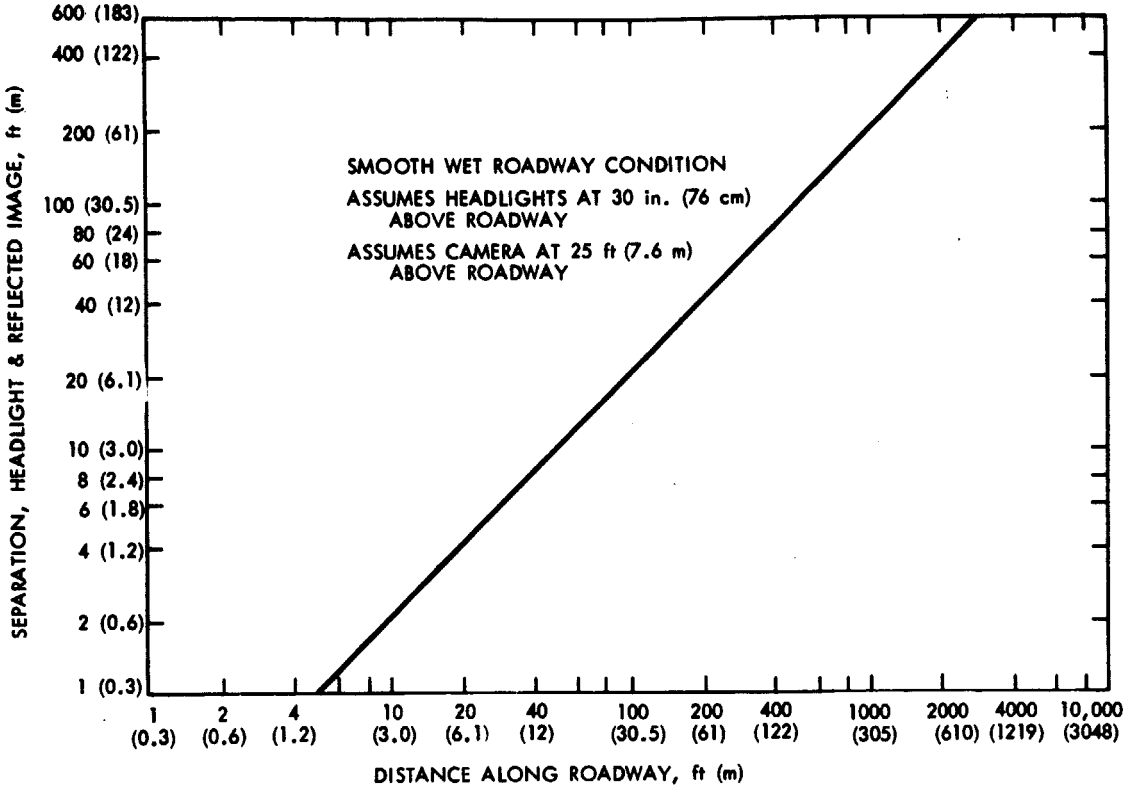

Figure 4-10. Reflected Headlight Image Separation

Table 4-1 lists typical scene brightness levels for visible-light imaging. This extremely wide range (1.2×10^9) need not be imaged within the same scene; however, sunlight reflections from polished metal at about 2×10^8 and reflections from dark paint at about 525 ft-L will

Table 4-1. Typical Scene Brightness Levels

Sun's disk	6×10^8 ft-L
Sun's reflection in windshield	5×10^7
Auto headlights	2×10^3
Auto taillights	4×10^1
Concrete roadway at noon	4×10^3
Concrete roadway at sundown	2×10^1
Concrete roadway, headlight-lit	5×10^{-1}

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occur within the same scene. This is a range of about 4×10^5. Images of the bright reflections may be usefully clipped by sensor saturation, if the bright region does not bloom into adjacent areas and obscure the picture. Nighttime scenes typically range from 2×10^3 for headlights to 5×10^{-1} for a roadway illuminated by headlights: a range of about 4×10^3. The WADS sensor must be able to adapt its sensitivity by a factor of about 10^4, in addition to having a direct dynamic range of 10^3.

The visibility of vehicles on a roadway by visible light is extremely high at night; headlights or taillights are very easily distinguishable by a thresholding algorithm against the relatively dark roadway. Visibility by daylight is also quite good, but will require a more capable algorithm than for the nighttime condition. The passage of a vehicle by daylight (as seen in visible light) is signaled by a sequence of local reflectance disturbances which may be as great as an increase by twice from metal trim, a decrease by 10 times or more from shadows under the car and within the passenger's compartment and an indeterminate change due to the vehicle's paint, which may have an equal, lesser or greater reflectance than the roadway. The precise sequence of changes will vary greatly, depending on the individual vehicle, sun angle, and weather conditions; but significant changes will occur which make individual vehicles readily identifiable.

Visibility, as noted earlier, is also a function of the scene irradiance level. Under conditions of low illumination, as at the beginning and end of the day, if the illumination level should be near the bottom of the dynamic range of a visible sensor, then vehicular shadows would be less identifiable. We should require that the WADS sensor, if a visible-light imaging sensor, have adequate sensitivity to image traffic at light levels below the lowest expected conditions. The principal question is: At what maximum light level are vehicle lights still in use? Figure 4-11 illustrates the results of tests conducted on the Santa Monica Freeway in Los Angeles in the fall of 1976 to measure the percentage of vehicles with lights on as a function of roadway brightness. The data showed some spread for vehicles driving toward the sunset or sunrise as opposed to those driving away for the higher light levels, but converged at lower levels. A tendency was also noted for hysteresis: lights tended to remain on longer at dawn; lights were left off longer at dusk. The bottom line of the test data was that 95% or more of the vehicles were using headlights at road surface brightness levels of 1 ft-L or less for all tested conditions. We conclude that the WADS sensor, if a visible imaging sensor, must be sensitive enough to sense images of scenes at 0.1 ft-L in order to adequately cover the dawn and dusk transition periods.

COMPARISON OF IR TO VISIBLE LIGHT IMAGING

In this section the specialized techniques and hardware needed to obtain infrared images are described, and some trade-offs that may be encountered in comparing infrared and visible light approaches are briefly summarized.

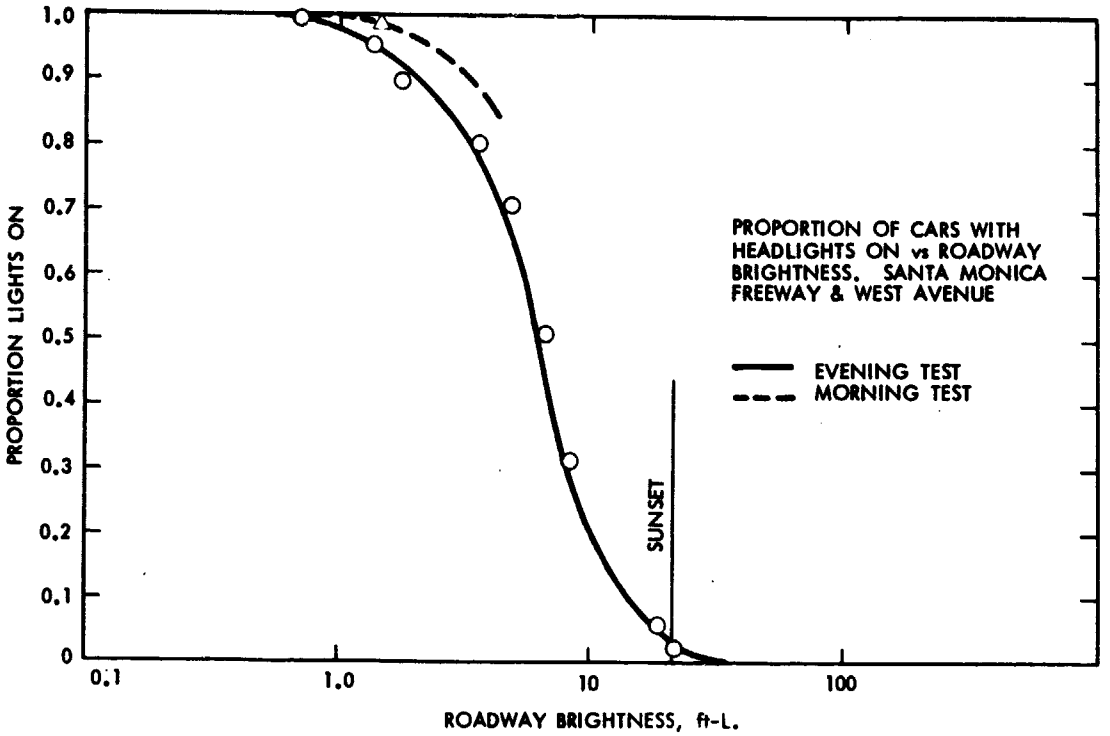

Figure 4-11. Traffic Headlight Survey

External to the imaging system, or camera proper, there will be essentially no difference between an IR WADS sensor and its visible light equivalent. Video output signals can be compatible. The difference lies in the nature of the IR image, and, as earlier discussed, in differences in scattering along the path between object and camera brought about by the longer wavelength of the IR radiation.

Thermal IR imaging devices typically operate in the 8-14μ range; wavelengths are roughly one order of magnitude longer than visible light. The principal source of radiation in this range is thermal self-emission, not reflected sunlight; thus the name thermal IR. The intensity of radiation from any surface, which is interpreted as brightness by the imaging sensor, depends partly on the surface (emissivity) and partly on its absolute temperature. Differences in temperature in a typical scene are of the order of 1-10°C, and of course can be caused by solar insolation (absorbed solar heat) or by energy dissipating objects, such as a hot exhaust pipe or a running tire.

The thermal image is simply a map of temperature at all points in the sensor field of view, in which temperature is represented by a corresponding grey-scale in the image. Subjectively, a thermal image often resembles a negative of a conventional photograph, in that objects we expect to be dark are sometimes white, and vice versa. Examples of IR

images are shown in Figures 4-12 through 4-14* (Ref. 4-9). The first photograph was taken in late afternoon; the last after sunset. IR images can also be obtained at night with no visible illumination being present, because temperature differences due to stored heat remain, and because of different cooling rates by radiation for individual surfaces. Figures 4-13 and 4-14 were taken after dark and are not qualitatively different from Figure 4-12, which was taken during daylight.

Another characteristic of IR images is that sunlight shadows of moving objects (like automobiles) are not pronounced, a factor that could reduce demands on the WADS recognition and tracking algorithm. As noted, nighttime images are qualitatively similar to daytime pictures. They are not identical, because the thermal environment is different at night - for example, the pavement surface is cooler than the air, rather than the reverse. However, the transformation from full vehicle image in the daytime to a head- or taillights-only image at night does not occur.

Finally, the dynamic range between average image intensity and the solar disc or directly reflected sunlight is much less in the IR than in the visible. Further investigation would be needed to establish quantitative levels, but the dynamic range present in views toward the rising or setting sun may not cause difficulty in IR. Direct viewing of the solar image does not damage an IR imager.

Unfortunately, we have not obtained good examples of IR images of moving automobiles. Figure 4-15** (Ref. 4-10) is an image of a car which is obviously parked, as shown by the warm side which is the sunlit side. However, we have seen images of moving cars and the following observations can be made:

(1) The IR image of a moving car "looks" like a car. Hot areas over the engine do not dominate the image. In fact the surface of a car at freeway speed appears cooler than the mid-afternoon pavement, with no apparent hot areas around the hood or radiator.

(2) The tires and portions of the running gear that can be seen show as saturated hot (pure white). Generally, the underside of a car appears hot.

(3) Where visible, that is, on a small percentage of the vehicles, exhaust pipes or mufflers were intense sources. VWs, in particular, appeared to show a hot exhaust system and engine under the rear of the vehicle.

The advantages that we see for an IR WADS imager are, first, the decreased scattering, making possible longer visibility range under certain conditions, particularly in smoke or haze; and, second, a less variable image between day and night.

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*Courtesy of Honeywell Electro-Optical Systems Division, Lexington, Mass.
**Courtesy of J. Perry, USN Night Vision Laboratory.

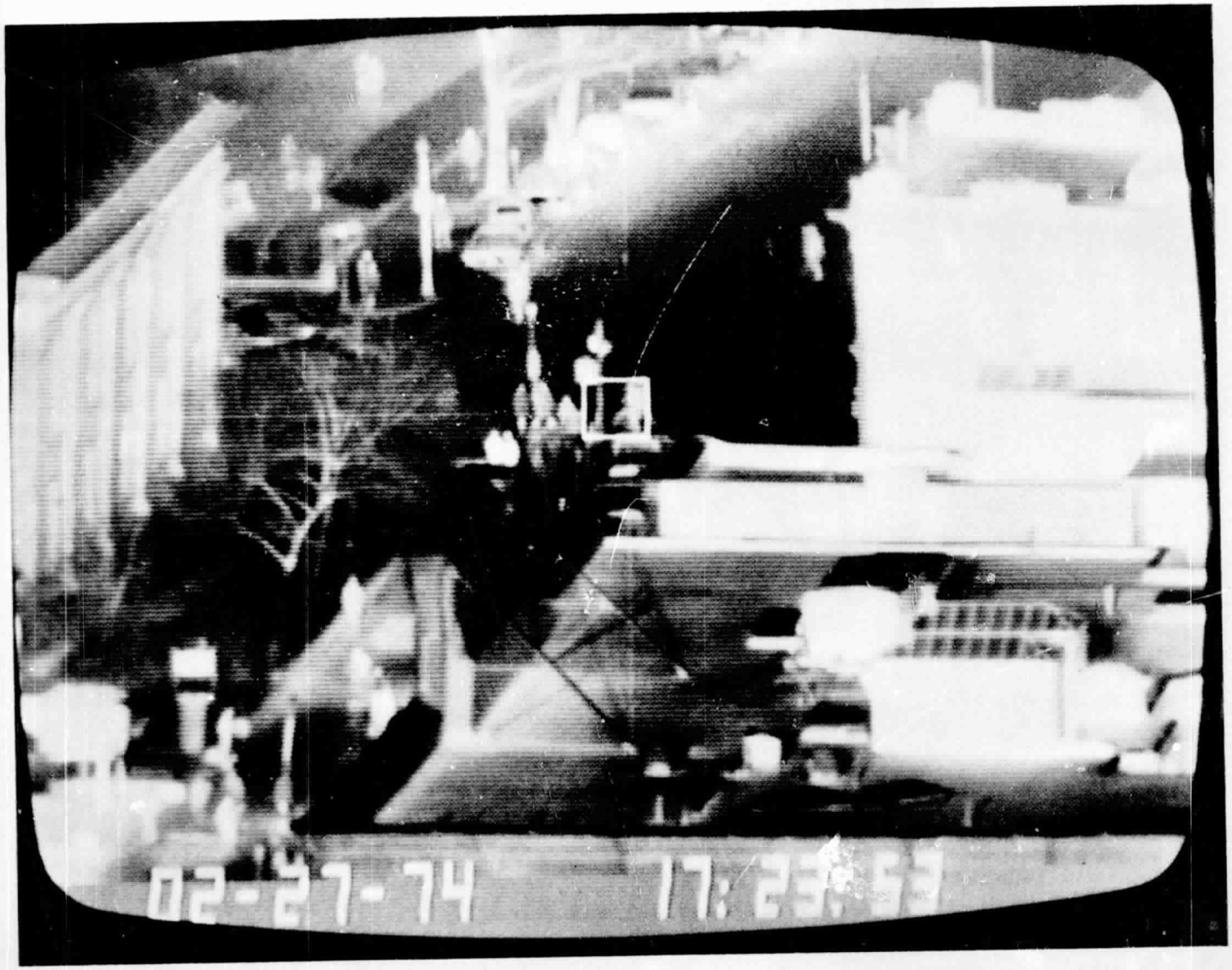

Figure 4-12. Thermal Infra-Red Image of an Urban Scene (Daylight) (Ref. 4-9)

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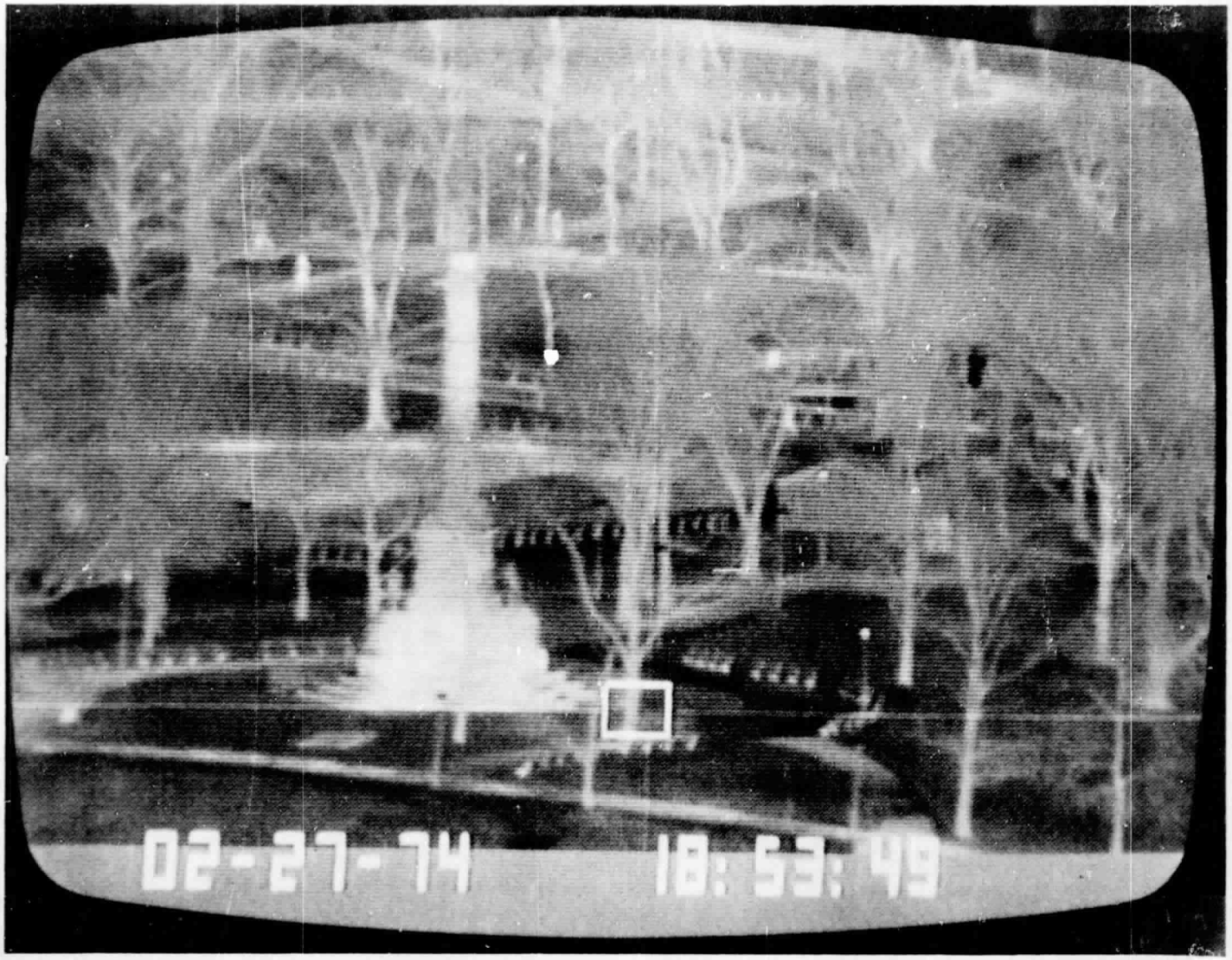

Figure 4-13. Thermal Infrared Image (Ref. 4-9)

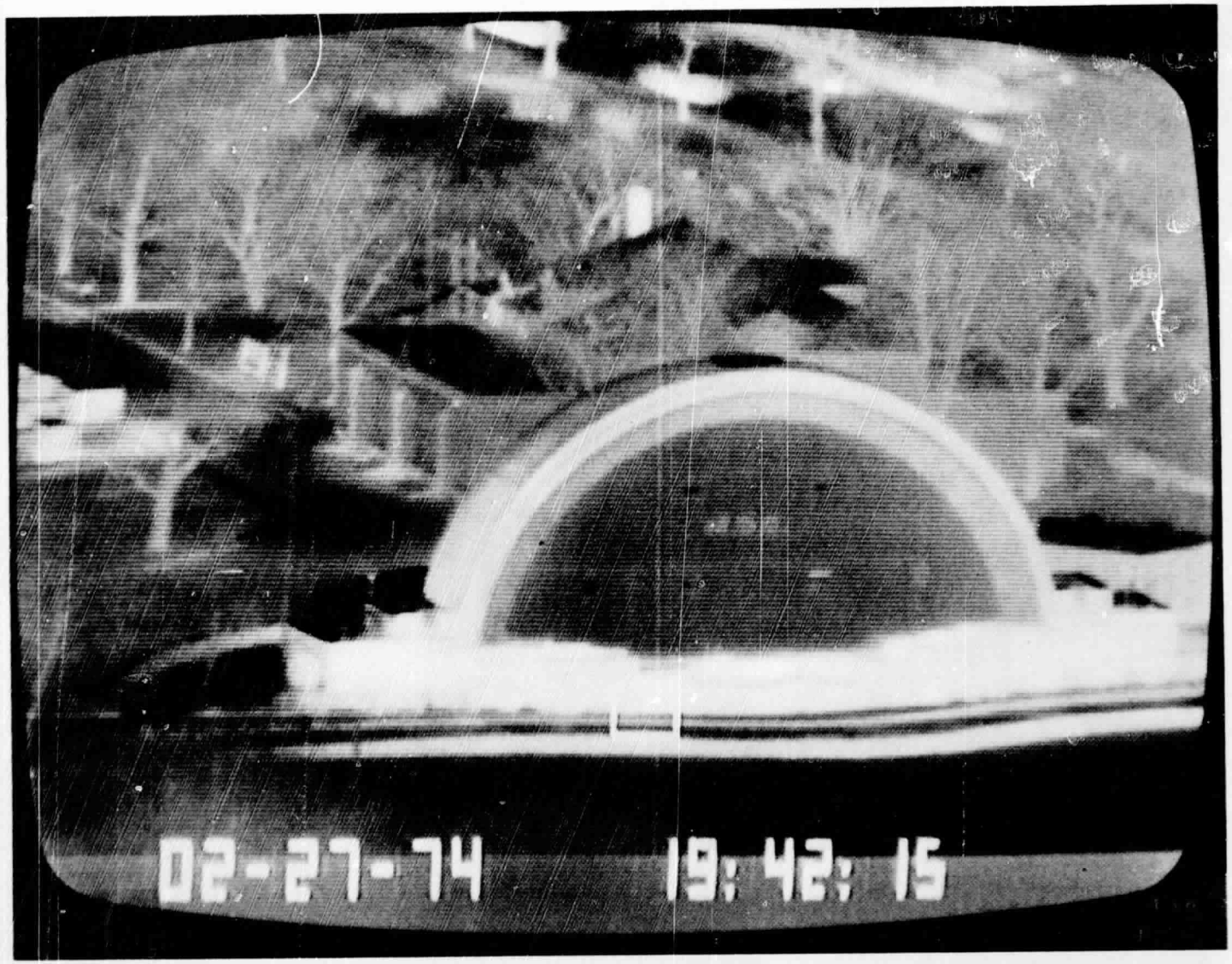

Figure 4-14. Thermal Infrared Image of an Urban Scene (Night) (Ref. 4-9)

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Figure 4-15. Thermal Infrared Image of a Parked Car. Sunlight has warmed the near side.

Contrasted against these useful characteristics is cost, which at present is at least an order of magnitude too high. Further discussion of these factors is given in subsequent sections.

IR IMAGING TECHNOLOGY

Infrared image sensors, like visible-light TV cameras, are scanning devices that strip information from the image in a serial manner. In IR imagers, the scanning is done by one of two means, mechanical or electronic. The mechanical scanners have been brought to a very sophisticated state of development for military applications, and generally it is that type of imager that is usually referred to as a FLIR (Forward-Looking Infrared).

Recently, commercial developments have succeeded in incorporating a thermal-IR sensitive surface into a conventional vidicon. The result, the pyroelectric vidicon camera, is a possible alternative to the FLIR system. A third sensor type, the Plumbicon or near-IR vidicon, is mentioned, but its spectral band is close to the visible, and its performance would not differ significantly from a conventional silicon vidicon.

Mechanical Scanners

In mechanical scanners, a detector is exposed to each element of the image by moving the image past the detector by optical means. As the detector is exposed to successive picture elements, a serial stream of information is produced, analogous to a standard video signal.

Two-dimensional mechanical scanners have been developed for IR imaging systems. Some are capable of operating at TV frame rates (30 per second), although a lower frame rate may sometimes be used to ease the requirements on the mirror scanner.

A basic limitation on a mechanical scanner of this type is that the detector is only able to look at a given picture element as it scans over that element. This is in contrast to a vidicon, in which each detector element averages intensity over a full frame time. Conflicting requirements result, for detector averaging time to achieve desired S/N, and frame rate. As a result, all high performance FLIR systems operating at or near the TV frame rate employ detector arrays. Multiple detector elements scan each picture element, and sophisticated signal processing is used to recombine and average detector outputs to form a single video output. Serial array, several detectors on one scan line, parallel array (one detector per scan line) and two-dimensional array geometries have been used.

For the thermal IR region, the detector or detector array must be cooled. Closed cycle refrigeration systems, Joule-Thompson (expanding gas) coolers, or liquid nitrogen can be used, but in any case the cooling system is a major part of the overall camera system.

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The cryogenic refrigerator used in mechanical scanners is a significant cost item. The cost of these devices ranges from $4K upwards. Intuitive thinking leads one to believe the refrigerator is the least reliable element in such a camera system, but in general mean-times-between-failures range between 500 and 33,640 hours. Typical values are approximately 3000 hours. Preventive maintenance at regular intervals is frequently practiced. As with detectors, a great variety of models of refrigerator and detector mounts exist from which to choose; the choice is truly a system consideration.

Pyroelectric Vidicon Sensors

Thermal vidicons employ a surface that changes its surface electrical charge in response to a change in temperature, a property of pyroelectric crystals. Triglycine sulfate (TGS), a ferroelectric insulating crystal, is typically used. A thin disk cut normal to the crystal axis forms the detector, and radiation from the scene is imaged on the crystal surface, creating a thermal image. The pyroelectric coefficient of TGS is sufficiently high to be effectively used to detect the resultant minute temperature changes, and its dielectric characteristics are consistent with maintaining the change in surface charge long enough for the readout process to be completed. The pyroelectric coefficient of TGS is related to its ferroelectric properties, and since the ferroelectric transition occurs at 46°C, the TGS vidicon cannot function if its faceplate exceeds that temperature, even temporarily.

A unique and possibly useful characteristic of the pyroelectric vidicon is that it cannot see stationary objects. Since the mechanism of reading out the thermal image involves creating tiny local charges on a capacitor formed by the TGS faceplate as a result of temperature changes, a pyroelectric vidicon has no d.c. response. The fixed portions of the image (roadway, signs, fences, etc.) will not appear in the image, but moving objects (vehicles) will. To obtain an image of the fixed background, the camera lens can be fitted with a light chopper, or the camera can be panned across the image. Either technique will bring out the background image.

The pyroelectric vidicon, being a bolometric detector, operates uncooled. Basic considerations related to thermal diffusion create a trade-off between sensitivity and resolution. Current practical devices typically operate at 200-line resolution. Note that a pyroelectric vidicon camera output is compatible with conventional TV; resolution and readout format are independent quantities.

Military and Commercial Developments

Development of high quality thermal IR imagers has resulted from very large military programs. For the most part, the quantitative results of these programs have been and are still classified. No classified discussions have taken place during the preparation of this report since, of course, classified information or hardware could not be used in a traffic monitoring system.

However, some of the technology is beginning to find its way into the commercial world. It is these products which we have looked at, and which are described in further detail below. Our view of the very complex technology is necessarily limited, but we feel the devices we have seen are representative of what can be done. An aspect of the subject that is not discussed further is the development of modular FLIR. This is a large and relatively new military program aimed at lowering system cost through standardization of components. FLIR systems would be made up of interchangeable modules or building blocks, in such a way that a wide range of uses could be satisfied by the same building blocks. The volume being considered is large, and the primary impact will be to reduce cost.

FLIR type IR imaging devices are being tested in a variety of non-military applications. For example, in Los Angeles, the U.S. Forest Service is actively pursuing the use of infrared imaging devices for surveillance of forest fires. The purpose is to locate hot spots and for perimeter definition, through the ever-present smoke cloud. In separate experiments, telemetry of line scanner data to fire command posts has also been successfully demonstrated. A similar activity is under way at the Canadian Forestry Service using infrared vidicon systems (Ref. 4-10).

In other areas, thermal signatures have been used in industry for a variety of purposes. Potential hazards in mining operations are detectable by thermal differentials caused by fissures in tunnel walls or ceilings which could affect structural integrity. Motors, bearings, transformers, can be monitored for thermal patterns indicative of potential failure. Hands-on inspection, which is sometimes dangerous in inaccessible areas, can be supplemented through use of an IR imaging system.

Other than these diagnostic activities, IR imagers can be used by plant security and fire departments, to assist in viewing in dark or smoky environments. Ecological thermal surveys can be done by IR observations, and in the field of medicine, thermal image displays yield useful information in diagnosis.

Our impression is that a great deal of interest exists in IR imaging techniques, but high unit costs limit the intensity of pursuit. However, if these private sector applications should develop into a significant market, the cost of commercial product thermal imaging devices could eventually fall to a level which would be of interest for the WADS application.

DESCRIPTION OF AVAILABLE IR IMAGING HARDWARE

A number of IR imaging systems are described below to give an indication of the types of systems available commercially and what kind of performance might be expected.

FLIR

An IR imaging system called HIPOD FLIR was demonstrated to JPL representatives by Hughes Aircraft Co. of Culver City, Calif. Designed for aircraft use, it is a serial scan imager having a space stabilized, fully turreted mount pointable over nearly a full hemisphere. This system has been extensively tested in an aircraft for nearly 4 years.

Its video format presents 315 lines interlaced at 30 fields and 15 frames per second. The detector is a single array of 25 HgCdTe detectors in serial-scan format. Resolution with a $2.3^{\circ} \times 3.0^{\circ}$ field of view lens system is about 0.25 minute of arc, corresponding to about 250 lines per frame. The system weighs 169.1 pounds (76.7 kilograms) and averages 397 watts with peaks to 539 watts. This system is representative of declassified military FLIR technology; its cost is in excess of $100K.

Mini-FLIR Systems

Philco-Ford, Newport Beach, Calif. and Minneapolis Honeywell market a compact, lightweight FLIR system representative of the most recently available technology. These Mini-FLIR systems cost about $100K at the present time.

The Aeronutronic Mini-FLIR is a sensor developed for remotely piloted airborne vehicles. The scanner, without cryogenics, is 4 inches (10.2 centimeters) in diameter by 5 inches (12.7 centimeters) long, weighing 3.5 pounds (1.6 kilograms), to which a refrigerator and three sets of telescope optics for different fields of view must be added. The HgCdTe detector arrays are cooled to 77°K and cover the 4 to 14 micron spectral band. The full-up system weighs 47 pounds (21.3 kilograms) and requires 200 watts at 28 Vdc.

The system output is fully TV compatible, having a 525-line raster at a field/frame rate of 60/30 per second. The basic scanner employs 0.45-inch (1.14-centimeter) diameter optics and has a spatial resolution of 2 milliradians with a field of view of $30^{\circ} \times 40^{\circ}$, or a 250 line resolution. The gimballed optics pointing system is stabilized for flight applications. The minimum resolvable temperature (MRT) is 0.2 to 0.4°C.

Probeye

Hughes Industrial Products Division in Costa Mesa, California, markets the lowest priced IR imaging system, Probeye, which presently costs $6K. Unfortunately, Probeye has little applicability to WADS as currently configured, because no electrical signal output is provided, and because of its poor resolution. The system is a self-contained, battery-operated IR viewer in a weather-resistant 6 x 8 x 9-inch (15 x 20 x 23-centimeter) case weighing 7.2 pounds (3.3 kilograms). The MRT for an object at 22°C is 0.1°C. The detectors are cooled with an argon Joule-Thompson device, for which one gas charge will last about 4 hours. Rechargeable batteries supply the 1.5 watts of power required.

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AGA Scanner

The AGA (AGA Inc., Taby, Sweden) single detector system is tailored for laboratory activities, and can be purchased for about $40K.

The AGA scanner uses a cryogenically cooled (-196°C) indium antimonide detector sensitive to the spectral range of 2 to 5.6 microns. The MRT specified for a 30°C object is better than 0.2°C. The higher performance system offered has a field/frame rate of 25/12.5 per second with 210 interlaced lines. This model and two portable models feature an isotherm function which highlights selected temperatures seen in the image.

Pyroelectric Vidicon Camera Systems

Pyroelectric vidicon camera systems have typically low resolution, fully TV compatible systems having sensitivity to wavelengths between 8 and 14 microns. Their MRT ranges between 0.15° and 0.4°. Sources for these systems are Amperex, which markets cameras made by Philips Laboratories, and the ISI Group of Albuquerque, New Mexico which markets for Thomson-CSF.

(1) Philips Laboratories - Amperex

The differences between a Philips Pyroelectric Vidicon camera system and a conventional vidicon television camera are principally in the optics and the pyroelectric vidicon itself. Some circuitry changes are also necessary. The camera has larger (IR) optics and forced ventilation ports are used to cool the power supply. Electronic changes in the camera include a modification of the preamplifier's bandwidth and sensitivity, a new high-voltage power supply card, a change from cathode to grid #1 vidicon blanking, and addition of a pedestal generator, variable position damp pulse, circular blanking, horizontal sawtooth shading corrector, a momentary poling switch, and a beam on-off switch. The primary purpose of these changes is to neutralize charge accumulation on the detector surface that is peculiar to the pyroelectric type of vidicon.

Without a lens system, the Philips camera measures 8 x 10 x 12 inches (20 x 25 x 30 centimeters) and weighs 14 pounds (6.3 kilograms); power requirements are 30 watts at 115 Vac.

The pyroelectric vidicon camera must be panned or the image must be chopped in order to make a fixed background visible. Panning tends to lose straight line elements in the image lying along the pan direction, and chopping produces a flicker that may be annoying to an observer unless processed out. Chopping also reduces the effective system sensitivity slightly. Typical performance yields an MRT of 1°C at about 160 TV lines resolution.

The present cost of the above system for a single unit, excluding the lens, would be about $7000, with delivery in 3 months.

(2) ISI Group (Thomson-CSF)

Most of the discussion above applies equally to the ISI pyroelectric system. The notably different characteristics are: bandwidth is 3.0 MHz, size (less lens) is 4 x 4.15 x 9 inches (10.2 x 10.5 x 22.9 centimeters) (no weight given), vidicon surface charge neutralization is by ion current in a soft vacuum in the vidicon. System cost without lens is about $9400.

IR Vidicon Camera Systems

These systems, in most respects, are identical to visible-light systems, the differences being only in spectral response attributable to the vidicon. As such, further system performance discussion will be deferred to the sensor discussion below, except for noting that such IR vidicons cost about 2 to 10 times as much as a visible vidicon.

Table 4-2 compares the commercially obtainable IR systems with a typical visible spectrum system. The projected costs are based upon quantities in the thousands. The pyroelectric camera may be the most attractive of the IR systems in spite of its reduced resolution, since it requires no cryogenic cooling and has a lower price. However, visible imaging cameras with full 525 line resolution are expected to be lower in cost by $2K to $4K.

Table 4-2. Comparison of Visible and IR Systems

Choice	System	Wavelength (microns)	Resolution	MRT (^{o}C)	Rate (sec^{-1})	Future Estimated Cost in Quantity ($K)
1	Visible	0.4-0.7	525 TVL	---	60/30	1-2
2	Pyroelectric	8-14	200 Lines	0.15-4°C	60/30	4-5
3	FLIR	8-14	420 Lines	0.2-0.4	60/30	20-30
4	Probeye	3-4	60 Lines	0.1	"No flicker"	4-6
5	Thermovision	2-5.6	210 Lines	<0.2	16-25	20-30
6	PbS-PbO Vidicon	0.4-2.4	525 TVL	---	60/30	2-3

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IR Optics

Special optics are required for a thermal IR camera because all glasses are opaque in this spectral range (8-14 microns). IR optics typically use germanium, but silicon or other IR transparent crystalline materials can be used. Reflective lens systems can also be made, but are less common. The index of refraction for these materials is much higher than for glass; this characteristic necessitates careful anti-reflection coating to reduce the Fresnel reflection losses at each surface. Without coatings germanium would lose 36% of the incident energy per surface. Transmission losses are also significant in these materials, losses ranging between 0.2% to 2.5% per millimeter.

As a result, an IR lens is considerably more expensive to produce than a visible-light lens of similar characteristics. IR zoom lenses, although available, are limited in zoom capability. If a variable field of view is necessary, a lens turret is the preferred approach.

A summary of available IR lenses is included in Table 4-3 for reference purposes.

TRADE-OFF CONCLUSIONS, IR VS VISIBLE IMAGING

In the WADS application, the trade-off between IR imaging and visible light imaging appears to involve a number of incremental improvements offered by the IR, balanced against a cost impact that, at present, is very large. There will always be a cost penalty for an IR system, if for no other reason than that cooling and exotic optics seem to be required. Although costs of present FLIR systems are not likely to drop quickly, because the technology is not really new, and military volume is quite large, technology advances may occur that will change the cost picture in the longer range. An example of such a possibility is development of an IR CCD sensor externally compatible with a visible-light CCD camera. If such a device were to appear, the potential for reduced cost is clear. Accordingly, the cost factor in the WADS application should be reexamined from time to time.

We have concluded that IR images equal in quality to commercial TV standards can be obtained now with the best technology. Reduced resolution or reduced frame rate as indicated in several of the examples in Table 4-2 above appear as disadvantages, but these factors should be viewed as part of the cost performance trade-off already mentioned. It may well be that on a cost-benefit basis an optimum IR WADS would use a lower resolution imager.

As we have seen, the often-quoted advantage of IR, that it can penetrate bad visibility, is only partially true. A more correct statement would be that an IR camera is never worse in poor visibility than a visible light camera, and it can be very significantly better under certain conditions. These conditions involve aerosols with small (<1 micron) particle size, such as smoke and haze.

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Table 4-3. Germanium Infrared Lenses for 8-14 Microns

Manufacture/ Type Number	EFL	f/#	FOV	Field D	T# Max	5 lp/mm	10 lp/mm	15 lp/mm	20 l/mm	List Price (Small Quantity)
SPACE OPTICS RESEARCH LABS, 7 Stuart Road, Chelmsford, Mass., 01824										
IRWS-OFH2.85	1.7" (44mm)	0.85	21°	16mm	.9	.83	.55	.45	.38	$2425.00
IRWS-OFH3.8	2.4" (62mm)	9.8	15	16	.85	.74	.53	.45	.35	$2800.00
IRWS-OFH21.5	3.0" (76mm)	1.5	12	16	1.85	.80	.75	.69	.60	$2030.00
IRWS-OFH4.8	3.2" (82mm)	0.8	11	16	.85	.74	.53	.43	.34	$3200.00
IRWS-1FH4.8	3.2" (82mm)	0.8	11	16	.85	.85	.80	.71	.64	$4050.00
IRWS-OFH31.5	4.5" (115mm)	1.5	8	16	1.6	.83	.76	.68	.60	$2700.00
IRWS-OFH41.5	6.0" (153mm)	1.5	6	16	1.6	.87	.80	.74	.65	$2950.00
RANK PRECISION INDUSTRIES, INC., 411 East Jarvis Avenue, Des Plaines, Ill., 60018										
IRTAL-1	100mm	1.0	-	16mm	-	.15	-	-	-	$2350.00
IRTAL-2	100	1.0	9.2°	16	1.1	.65-.90	.25-.75	-	-	$3000.00
IRTAL-3	100	0.7	10.3	18	0.8	.85-.90	.55-.70	-	-	$9300.00
IRTAL-4	50	0.7	18.2	16	0.8	.55-.95	.25-.85	-	-	$3000.00
IRTAL-5	30	1.0	30.9	16	1.1	.60-.95	.10-.90	-	-	$2000.00
IRTAL-5 Austere	.30	1.0	30.9	16	1.1	-	-	-	-	-
In Devel	200	1.0	-	-	-	-	-	-	-	-
In Devel	300	1.5	-	-	-	-	-	-	-	-
Zoom	50-200	1.0	-	-	-	-	-	-	-	(Wreathall Mount $175 addit.)
ZOOMAR, INC., 55 Sea Cliff Avenue, Glen Cove, L.I., NY, 11542										
IR-50	50mm	0.8	20°	18mm	-	.55-.90	-	-	-	$2500.00
IR-80	80mm	0.8	13	18	-	-	-	-	-	$8000.00
IR-100	100	1.0	10	18	-	.35-.90	-	-	-	$4500.00
IRHS-100	100	0.7	10	18	-	.70-.90	-	-	-	$7000.00
IR-140	140	0.7	8	18	-	-	-	-	-	$12000.00
IE-270	270	1.35	4	18	-	.90-.95	-	-	-	$18000.00
IR-2X30	30-60 Zoom	0.8	33-16.5	18	-	-	-	-	-	$6500.00
IR-2X50	50-100 Zoom	1.0	20-10	18	-	-	-	-	-	$8000.00
IRCAT-250	250	1.0	4	18	-	.30-.75	-	-	-	$6000.00
IRCAT-2X125	125-250 Zoom	1.0	8-4	18	-	-	-	-	-	$7500.00
J. H. DALLMYER, LTD., Church End Works, High Road, Willesden, London, NW-10-2D N, Great Britain										
IR Lens	50mm	0.8	20°	18mm	-	.90-	.75	.60	.50	£950 (FOB London) (Wreathall Mount avail.)
PILKINGTON P.E. LIMITED, Glascoed Road, St. Asaph, Flintshire, LL17 OLL, Great Britain										
HAIR	200mm	1.31	5.2°	18mm	1.42	.91	.72-.80	-	.40-.50	
OLD DELFT CORP. OF AMERICA, 2735 Dorr Avenue, Fairfax, VA, 22030										
F50-f1.0	50mm	1.0	-	20mm	-	.88-.94	-	-	-	-
MATRA DIVISION OPTIQUE, 93 Av Victor-Hugo, 92503 Rueil-Malmaison, France										
INFRA ROUGE	50mm	1.0	-	-	-	-	-	-	-	-Fr Frs 18,000 (FOB Paris)

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In fog, the advantage of IR decreases, depending on conditions, and tends to disappear for dense, wet fogs. There can be no advantage for IR in blowing snow or rain. In any case, the visibility benefit of IR must be evaluated on a statistical basis for each particular location, based on meteorological data. The benefit, in general, will be an incremental one; i.e., the probability of outage due to reduced visibility only will be reduced, but in no case will it be eliminated.

Unique characteristics of the IR image should be noted, in case situations should arise in which they are particularly important. These include the lack of shadows and the greatly reduced glare in severe back-lighted conditions, as well as the characteristic of the pyroelectric vidicon which causes the fixed background in an image to vanish.

We conclude that, at present, it is difficult to justify the substitution of an IR imaging device for a visible light camera because of its greatly increased cost, larger by over one order of magnitude. However, the IR technology should be monitored in parallel to any visible-light WADS sensor development because the incremental advantages and unique characteristics of IR imaging may prove important in special situations. In addition, the technology may experience breakthroughs in the future such that system costs will approach visible-light system costs (perhaps within a factor of 2).

VISIBLE LIGHT IMAGE SENSORS

High resolution visible-light image sensors have developed rapidly in the last several decades. Impetus given by the demands of commercial television broadcasting, military needs, and most recently by the mass consumer market for closed circuit and taped video has led to the emergence of a wide selection of well-developed image sensors. Greatly improved sensitivity, stability, dynamic range and operating lifetime have resulted. Full television-compatible imaging is available from low-cost miniature image tubes. Solid state array image sensors have begun to arrive and promise a further miniaturization with even lower costs for the television camera.

This section of the report begins by discussing the general requirements that should be imposed on a visible-light WADS video sensor. The visible-light image sensors currently available are then briefly surveyed and several potentially useful devices now under development are discussed. Five selected devices are compared as to performance and one is recommended for the breadboard phase of the program.

It is believed that the following general requirements should be imposed on a visible-light WADS video sensor:

(1) The sensor must provide a picture compatible with standard commercial video at 525 lines and with a 2/1 interlace.

(2) The sensor, with a commercially available lens and automatic light control iris, must have a limiting capacity of

imaging scenes having a brightness of 0.1 ft-L. At the same time, the sensor must be capable of imaging automobile headlights.

(3) The sensor, with the same automatically controlled lens, must be capable of viewing the sun's disk repeatedly without damage. Under the same conditions, the sensor must be able to image sunlight reflections from vehicles without obscuring adjacent areas through blooming.

(4) The image sensor must be able to function through all climatic extremes of temperature.

(5) The sensor should not exhibit a residual image characteristic great enough to interfere with contrast discrimination of moving targets.

(6) The sensor should be one which is or will be in large scale production in response to a commercial market.

(7) The sensor's projected initial cost and maintenance/replacement cost must be consistent with the WADS cost guidelines.

Table 4-4 lists a number of television image sensors now available and under development. These sensors encompass a variety of technologies; all but the last two entries are vacuum tubes with electron beam guns. Several utilize photocathode emission for image conversion, the rest utilize photoconduction. Image intensification by electron acceleration is employed in several, and two are fully solid state image-sensing microcircuits formed on silicon chips.

The discussion which follows is confined to five candidates: the antimony trisulfide vidicon, the silicon diode array vidicon, the "Newvicon" vidicon, the charge coupled device, and the charge injection device. The others listed in Table 4-4 will not be discussed for reasons of high cost, fragility or inappropriate characteristics.

The various vidicons differ chiefly in the construction of their targets. All use semiconductors. Figure 4-16 illustrates the construction. The only components within the vacuum tube are an electron gun, an electrostatic shield and grid, and the photoconductive target on the tube face. Magnetic focus, deflection, and alignment coils are mounted concentrically about the tube. Feedthroughs at the gun end provide filament power and acceleration voltages. A transparent ohmic contact at the face plate is made through the envelope to couple out the video signal.

Figure 4-17 illustrates details of an antimony trisulfide vidicon. At the beginning of an imaging cycle, the electron beam is scanned over the surface of the photoconductor target in a raster pattern, charging it to a uniform potential. The optical image generates a pattern of conduction currents in the photoconductor target. At the end of the exposure period, an analog of the optical image has been formed in the

Table 4-4. Typical Television Image Sensors

Type	Application	Comment
Image Orthicon	Commercial television in 1950s and 60s.	Insensitive. Narrow dynamic range. Has photocathode.
Secondary emission conduction (SEC)	Military. Low light level.	Fragile target. Damaged by illumination overload. Photocathode.
New Image Isocon	Commercial television.	Improved image orthicon. Wider range. More sensitive.
Plumbicon Vidicon	Commercial television.	Current TV standard. Wide range. Damaged by overload.
Vidicon	Closed circuit television (CCTV).	Standard CCTV. Lowest cost. Damaged by overload. Lags.
Silicon Diode Array Vidicon	Commercial. Low light level CCTV.	Immune to overload. Little lag. Very sensitive, wide range.
"Newvicon" Vidicon	Commercial. Low light level CCTV.	Heterojunction. Immune to overload. Very sensitive. MTBF not known.
Silicon Intensifier Target (SIT)	Military and commercial. Low light level.	Like SEC except target. Rugged. Wide range, very sensitive.
Intensifier Silicon Intensifier Target (ISIT)	Military and commercial. Very low light level.	SIT tube coupled to image intensifier tube.
Silicon Mosaic Sensors	Instrumentation, metrology.	Limited number of image elements. X-Y addressed.
Charge Coupled Device (CCD)	CCTV, metrology.	All solid state. Not fully developed.
Charge Injection Device (CID)	CCTV, metrology.	All solid state. Not fully developed.

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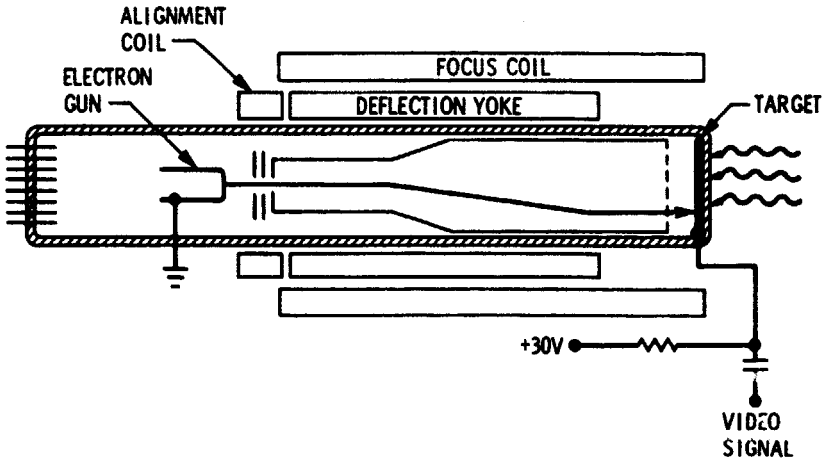

Figure 4-16. Vidicon Photoconductive Camera Tube

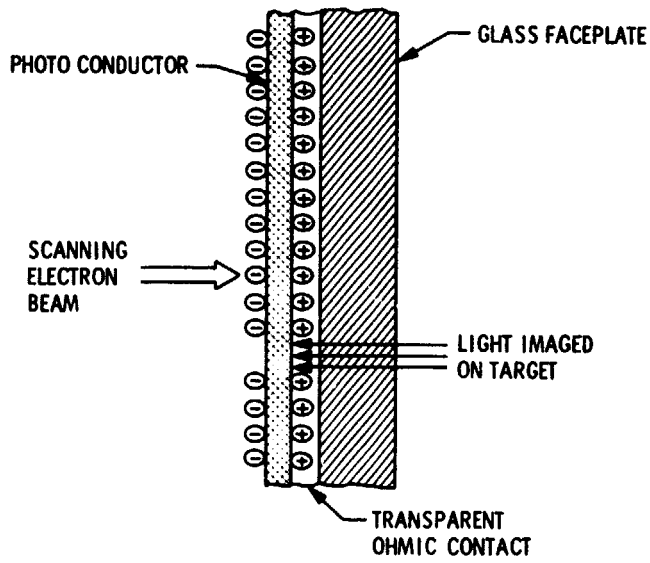

Figure 4-17. Antimony Trisulfide Vidicon Target

charge distribution on the inner face of the semiconductor target. The electron beam then rescans the target, recharging the surface to the original uniform distribution. Displacement currents drawn through the ohmic contact layer as the target is recharged carry the video information.

This configuration is very widely employed in miniature tubes for closed circuit television and video taping sets. The tubes have adequate sensitivity, 0.15 ft-L for an f/1.8 lens and good dynamic range, 10^3 or greater, exhibit very little blooming in response to saturation and are available in quantity at prices below $70 each. They do exhibit a large amount of residual image, 30% at the third image field after

exposure, can be damaged by exposure to very bright lights, and have an operating lifetime that is currently about one year. This tube is discussed here because it is very appropriate for test work under controlled conditions, although it cannot meet the requirements for an automatic WADS sensor station.

The silicon diode array vidicon is physically similar to the antimony trisulfide vidicon with the exception of the target (Figure 4-18). The target is a planar silicon photodiode array, fabricated photolithographically on a silicon chip. P-type islands are formed in an N-type substrate by diffusion through windows in a silicon dioxide layer. A "resistive sea" semi-insulator layer is typically applied over the face to prevent the oxide from acquiring and holding a charge. An N^+ region is formed on the far side of the chip, and this layer provides a bias connection. The individual diodes are back biased to a uniform charge level by the electron beam, as in other vidicons. Minority carriers generated in the substrate by the optical image during each integration cycle are collected in the adjacent diodes, reducing their charge. The image pattern is subsequently read out by monitoring displacement currents as the diode array is recharged by the electron beam.

The silicon diode array vidicon has a number of very significant advantages over antimony trisulfide target vidicons. Because the target is silicon, the quantum efficiency and spectral response range are much greater, yielding a greatly improved sensitivity. Using an f/1.8 lens a silicon diode vidicon has an imaging threshold below 0.03 ft-L target brightness. The target is not damaged by direct imaging of the sun and, if an automatic light control iris is installed, blooming can be extremely low. The field experience with cameras using this tube has been extremely good. Suppliers report they have very few repair calls on silicon diode array cameras, and estimate that mean tube lifetime is about 3 years of continuous use, as opposed to a year for antimony trisulfide vidicons.

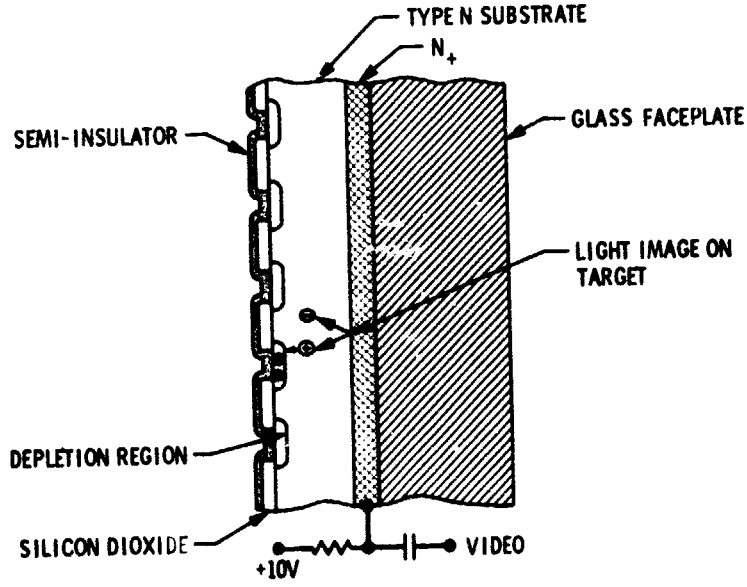

Figure 4-18. Silicon Diode Array Vidicon Target

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Partially offsetting these advantages are several negative factors. Because of the complex patterning required, fabrication yield is much lower and device costs are relatively high, about $475 at this time. Because of the discrete detector matrix, the modulation transfer function (resolution) is somewhat reduced at high spatial frequencies relative to that for a continuous target.

The "Newvicon" is one of several recently available vidicons which utilize heterojunction targets (Figure 4-19). A blocking and rectifying layer is laid down over a semiconductor on the electron beam side. The blocking layer prevents penetration of the semiconductor by the scanning electrons, so that a smaller bandgap semiconductor may be used. Holes generated by light absorbed in the semiconductor move freely through both the semiconductor and the blocking layer to neutralize the deposited charge. The blocking contact does not conduct laterally and there is little image spreading due to diffusion.

The Newvicon has only been on the market for a relatively short time. Lifetime is not yet known. Performance, however, is extremely good. It demonstrates a sensitivity equal to that of the silicon diode array vidicon, is not damaged by bright light overloads, and exhibits minimal blooming or residual image. Because the target is continuous, the image resolution exceeds that of the silicon vidicon. The price of the tube is presently high, $575; however, because of its comparable simplicity, the price should stabilize near that of a standard vidicon, at $100 or less, within a few years. It remains to be seen if the Newvicon will exhibit the long and trouble free lifetime of the silicon vidicon.

Two classes of all-solid-state image sensors have reached the market in preliminary states, the charge coupled device (CCD) and the charge injection device (CID). Both are formed by microcircuit techniques on silicon chips, and offer the potential of extreme operational simplicity, the ultimate in miniaturization and extremely high levels of performance. Neither has yet found the mass market necessary to bring the price down.

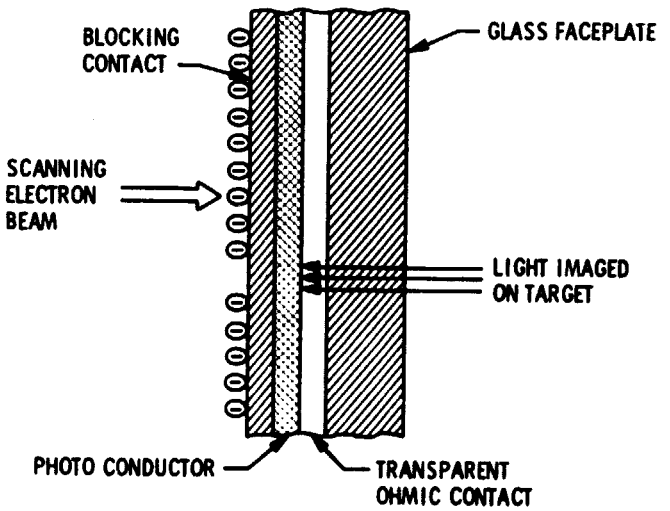
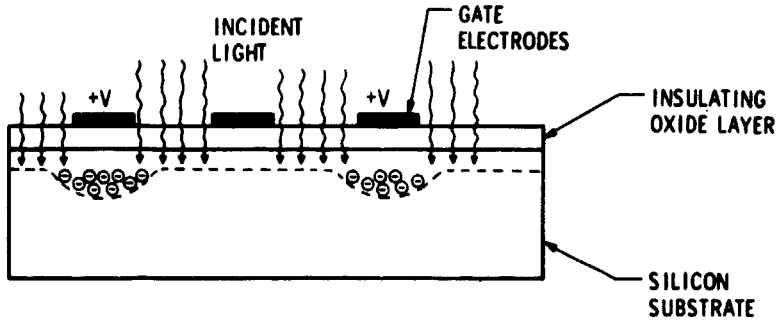


Figure 4-19. Heterojunction Vidicon Target

Figure 4-20 illustrates the basic concept of signal generation in a CCD. Gate electrodes are placed upon an insulating oxide layer over a silicon substrate. A voltage is impressed upon alternate electrodes, creating depletion regions in the silicon beneath. Signal charges generated within the silicon by photoionization are collected in the nearest depletion region. The pattern of charges then is a direct analog of the optical image which was incident on the CCD.

Figure 4-21 illustrates how the individual charge packets may be transferred to successive electrodes and so eventually to an output. The



OPERATION

1. INCIDENT LIGHT CREATES HOLE-ELECTRON PAIRS THRU PHOTO-IONIZATION OF SILICON
2. CHARGES ACCUMULATE IN POTENTIAL WELLS UNDER ENERGIZED ELECTRODES
3. CHARGE PACKETS REPRODUCE INCIDENT LIGHT PATTERN

Figure 4-20. CCD Charge Packet Generation

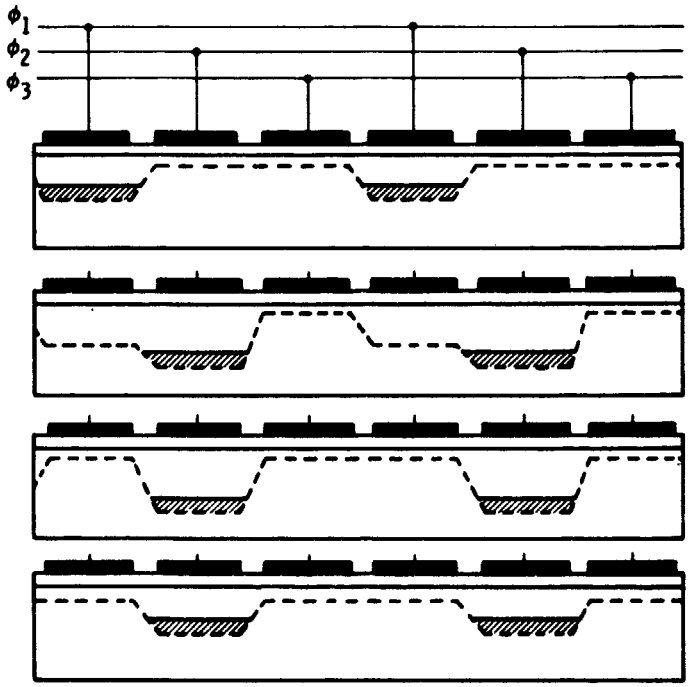


Figure 4-21. Three Phase Charge Coupling

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technique simply involves lowering the potential on an adjacent electrode and raising it on the one currently carrying the charge. The charge packet quickly moves to the lower potential. Then the potential is removed entirely from the original electrode, and reduced on the second. This is a three-phase operation, as illustrated, and it provides an unambiguous direction of transfer. The same result may be achieved with a two-phase structure if an asymmetry can be provided in each potential well to prevent backward flow of the charge. This is accomplished in existing CCD's by implanting charge barriers under part of the width of each electrode.

Figure 4-22 illustrates the structure of a linear CCD imager. Charge is generated in photosites which are defined by a serpentine photogate and a surrounding transfer gate. After completion of an integration period, the transfer gate is lowered and the charge from each photosite is transferred out to corresponding CCD shift register electrodes which lie on both sides of the photosites. After the charge packets have been transferred to the shift registers, then the charges are synchronously stepped along the registers and are reinterleaved at the output register into a serial analog data stream corresponding to the brightness levels of the image which was sampled by the photosites.

A variety of architectures have been implemented to extend this technology to area imaging arrays and to produce the necessary image field interlacing. One approach, used by Fairchild Semiconductor, transfers the image into shift register columns lying between columns of image sensors. The image is then shifted one line at a time into an output register. Alternate image elements are transferred into the registers in alternate fields, thus accomplishing the interlace feature. RCA CCDs transfer the entire image into a CCD memory matrix of size

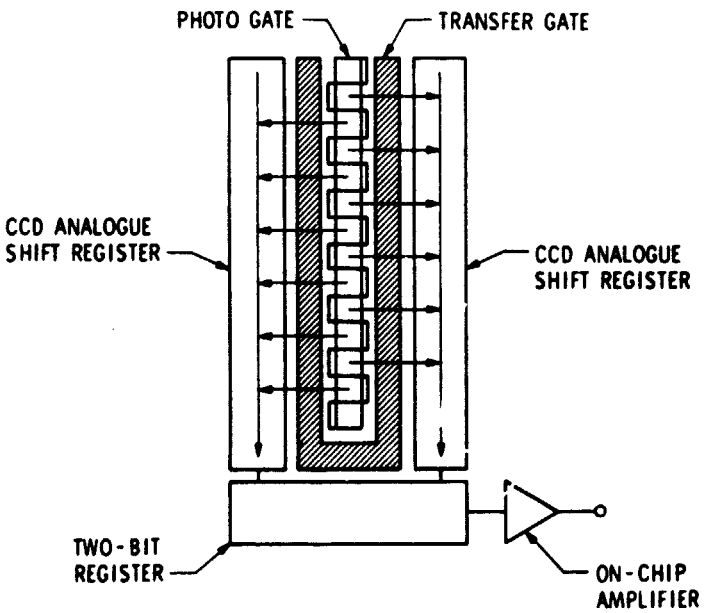

Figure 4-22. CCD Linear Imaging Device

equal to the picture sensing matrix. The images are then read out serially during the next integration period. Figure 4-23 illustrates a Fairchild 190 x 244 element CCD which has been mounted onto a standard 24 pin Dual Inline Package (DIP).

Four companies are known to be developing imaging CCDs: Bell Telephone, RCA, Fairchild Semiconductor, and Texas Instruments. Of these, only RCA has a fully television compatible CCD on the open market. The RCA CCD has an imaging matrix of 512 x 320 elements. The chip is a so-called "surface channel" device which has sensitivity comparable to that of an antimony trisulfide vidicon.

Fairchild Semiconductor is known to be developing a 490 x 388 element buried channel CCD which will be fully television compatible, and will be several times more sensitive than the RCA device. A buried channel CCD accumulates the charge packets in depletions formed within the bulk silicon, rather than at the surface, thus avoiding the high density of surface states which can act as traps. The Fairchild CCD is available in limited quantities, but has not been announced as a commercially available product yet.

Texas Instruments is developing back side illuminated CCDs which promise to be even more sensitive, but has not indicated any intention of marketing a device.

Bell Laboratories, of course, does not develop products for the open market.

A related solid state image sensor is the Charge Injection Device (CID) (Figure 4-24). This device is also a silicon microcircuit. Pairs of capacitors electrically connected in rows and columns are formed on a silicon oxide insulating layer. Charges generated by photoionization within the silicon are collected under one of the sets of capacitors. Signal readout of a specific element is accomplished by removing voltage from all the horizontally connected capacitors in that row by one scan register and from all the vertically connected capacitors in that column by the other scan register. Only for the selected element do both capacitors lose voltage. The stored charge at that site is then injected into the substrate and is detected as the signal.

This imager has been available for several years from G.E. The picture format is too small to be of interest to WADS at this time, approximately 200 elements squared. Sensitivity has been poorer than for the CCD, since the output capacity is relatively large. However, in other respects, imaging has been of very good quality. G.E. is pursuing ways of improving sensitivity and this device might become a very important imager.

Table 4-5 lists performance parameters of the four TV-compatible imagers that we have discussed. Notice that all (potentially) have adequate sensitivity, except the common (antimony trisulfide) vidicon. All have adequate dynamic range and only the vidicon is damaged by optical overload. The CCD as presently configured exhibits severe blooming characteristics; charges spill over into adjacent registers after

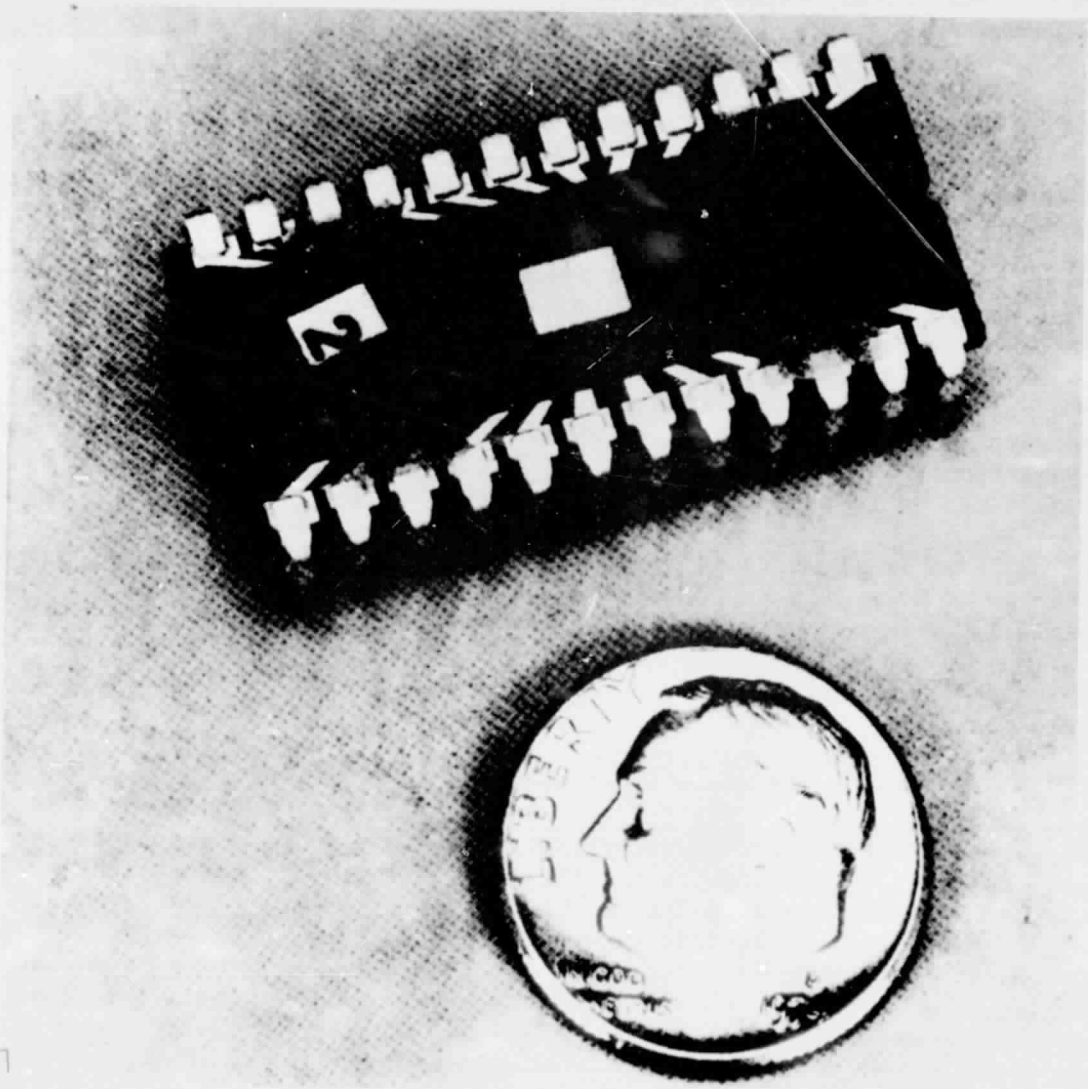

Figure 4-23. Charge Coupled Device (CCD)

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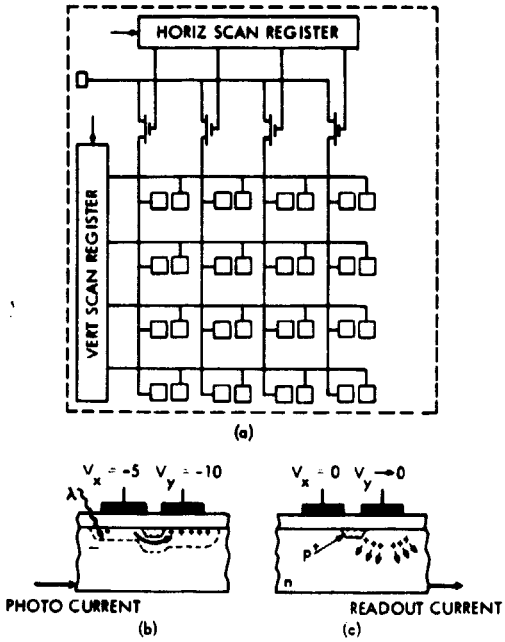

Figure 4-24. Charge Injection Devices

saturation is exceeded. The vidicon exhibits a substantial residual image, 30% remaining from any given image in the third field succeeding. Operating lifetime is only one year for the common vidicon and is unknown at this time for the Newvicon. Cost of the vidicon has probably bottomed out, at about $70, as it is well developed. Both the silicon vidicon and the Newvicon currently cost about $500; these prices will probably drop substantially as the devices and their markets develop. CCD costs reflect the absence of any substantial market at this time; however, we assume that demand will develop and prices will drop, to perhaps $500.

As a result of this comparison, the following recommendations are made:

(1) Use a standard vidicon camera for breadboard tests. It is less expensive, has better resolution than a silicon diode vidicon, and has adequate performance under controlled test conditions.

Table 4-5. Visible Image Sensor Trade-off

Imager	Sensitivity[1]	Dynamic Range	Overload Damage	Blooming	Lag[2]	γ	Probable Lifetime	Present Cost	Cost 3 Yrs	Maturity
Vidicon	0.15 ft-L	44 db	Severe	Minimal	30%	0.65	1 Year	$69.50	$69.50	Mature
Newvicon (Vidicon)	0.03 ft-L	43 db	No	Minimal	10%	1.0	Unknown	$575.00	$100.00	New
Si. Diode Array Vid.	0.03 ft-L	43 db	No	Low	10%	1.0	5 Year	$475.00	$200.00	Developing
CCD	0.01 ft-L	48 db	No	Currently[3] Severe	0	1.0	10 Year	($2500)	$500.00	Developing

NOTES:
1. Object brightness to provide useable picture.
2. Lag is residual image signal at 3d field, 33 msec.
3. Development in CCD's to control blooming.

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(2) Re-evaluate sensor candidates prior to initiating advanced work. Further development on CCDs will have occurred and experience with Newvicons will have been gained. Also, the impact of the car recognition algorithm upon sensor requirements will be better known.

The CCD (or CID) is potentially the most desirable candidate in the long run because of the all solid state construction. There appear to be no inherent wear-out mechanisms. However, at the present time, the silicon vidicon is the best choice, with the Newvicon becoming first choice if its operational lifetime proves adequate.

PRELIMINARY LENS SELECTION FOR WADS

In this section we will outline the basic requirements for the WADS lens and list available lenses, characteristics, and cost. This is only intended to be a preliminary assessment to determine that appropriate optics are available. A selection based on detailed requirements and tests of sample lenses should be made in a later program phase.

Preliminary requirements are:

(1) The lens must cover a 2/3 inch vidicon format.

(2) The lens must have zoom capability:

(a) Approximately 12-1/2 mm focal length, short end.

(b) 6/1 zoom range minimum.

(3) The lens should have the largest available aperture.

(4) The lens should have an automatic iris with a graded neutral density filter for a transmission ratio of 10^4 or greater.

(5) The lens should have the following functions motorized:

(a) Focus.

(b) Zoom.

(c) Iris.

The requirement for a 12-1/2 mm minimum focal length arises from an assumed need to cover six 14-foot (4.6-meter) wide lanes plus shoulders at a 100-foot (30.5-meter) distance. The 6/1 zoom provides resolution at 1/2 mile (805 meters) of 2 feet (0.6 meter), adequate for surveillance purposes.

Table 4-6 is a representative list of zoom lenses currently available for television cameras. Note that the most favorable f/number is f/1.8, and that a reasonable number have minimum focal lengths of 12-1/2 mm. Lenzar is the only American company listed, and has the

Table 4-6. Zoom Lenses for TV Cameras

Source	Focal Length	Zoom	f/No.	Motorized	Cost	Comments
Angenieux	9.5-142	15/1	f/2.5	No	-	
	12.5-188	15/1	f/2.5	Yes	-	
	14-210	15/1	f/1.8	Yes	-	
	20-80	4/1	f/2.5	Yes	$1185.00	
Canon	11.5-90	8/1	f/2.1	No	$ 400.00	
	11.5-90	8/1	f/2.1	Yes	$ 950.00	
	11.5-110	10/1	f/2.3	No	$ 600.00	
	11.5-110	10/1	f/2.3	Yes	$1100.00	
	12.5-50	4/1	f/1.8	No	$ 190.00	
	12.5-75	6/1	f/1.8	No	$ 300.00	
	12.5-75	6/1	f/1.8	Yes	$ 850.00	
Kowa	12.5-50	4/1	f/1.8	No	$ 139.50	$49.50 in lots of 500
	12.5-75	6/1	f/1.8	No	$ 199.50	$70.85 in lots of 500
	13-130	10/1	f/2.4	No	-	
Lenzar	12.5-62.5	5/1	f/1.8	Yes	$1095.00	Auto iris and filter
	14.8-90	6/1	f/1.8	Yes	$2075.00	Auto iris and filter
	14.8-150	10/1	f/1.8	Yes	$2775.00	Auto iris and filter
	18-90	5/1	f/1.8	Yes	$1535.00	Auto iris and filter
	30-150	5/1	f/2.7	Yes	$2975.00	Radiation hardened
Tamron	12.5-75	6/1	f/1.8	Yes	$ 861.50	
	14-140	10/1	f/1.9	No	$1195.00	
	14-140	10/1	f/1.9	Yes	$1725.00	
Cosmicar	12-72	6/1	f/2.3	No	$ 222.00	
	20-200	10/1	f/1.9	No	$1530.75	
	22.5-90	4/1	f/1.5	Yes	$ 930.00	
Schneider	18-90	5/1	f/2.0	No	$1335.00	
	18-90	5/1	f/2.0	Yes	$2232.00	

only zoom lenses with automatic iris and filter at this time. However, industry representatives point out that the built-in automatic iris and filter has just recently arrived for fixed focal length lenses, and will shortly be available for zoom lenses.

Table 4-7 is a cost element analysis using data from Table 4-6 and includes other data on fixed focal length lenses. Costs of three basic 12-75 mm manual zoom lenses are listed for an average retail price of $241. The costs of five lenses with and without motorization of the focus and zoom functions are compared. On the average, motorization adds $533, if we exclude one of the data points. (Schneider's cost increase for motorization is 65% greater than the average of the remaining sources.) Prices for fixed focal length lenses with and without an automatic light control iris and filter spot are compared in the last grouping. The average increase for four Cosmicar lenses is $188, the total of these average cost elements is $962.00. Assuming an industry wide markup equal to the Kowa stated markup from OEM prices to retail of 2.8, it can be expected that the WADS lens will cost about $341.50 in quantities of 500 or more. In quantities of 100, the lens can probably be obtained for $500 each.

We conclude that a suitable lens for next phase tests, the f/1.8 14.8 to 150 mm Lenzar, is currently available. The minimum focal length is a little longer than desired, but can be accommodated by a slightly longer minimum field distance. The 10/1 zoom range will allow the opportunity of comparing 6/1 and 10/1 zoom capabilities. Volume production lenses with the required characteristics should be available by the time a selection for production design must be made.

SUMMARY

It is concluded that imaging can provide a satisfactory means for obtaining traffic flow data under all weather and illumination conditions, but that the longer visual range traffic surveillance function will be impaired for many bad weather conditions. Thermal infrared imagers potentially offer advantages in terms of a simpler, more consistent image, but the cost of these units, now and in the forseeable future, is prohibitively high for the WADS application. Television cameras are available now which are suitable for WADS; however, it appears that an even better selection at more favorable costs could be made in several years. The required zoom lenses are available now at reasonable cost levels; however, the automatic iris and graded neutral density filter needed will probably not be available with the zoom lens for several years.

The prognosis for the WADS instrument is favorable from the standpoint of the imaging sensor.

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Table 4-7. Cost Element Analysis

Basic Lens Cost: 12-75 mm Zoom, Manual

• Canon	$300
• Kowa	200
• Cosmicar	222
Average	$241

Motorization Cost

• Canon	11.5-90 mm	$ 400 - $ 950	Δ = $550
• Canon	11.5-110 mm	600 - 1100	Δ = 500
• Canon	12.5-75 mm	300 - 850	Δ = 550
• Tamron	14-140 mm	1195 - 1725	Δ = 600
• Schneider	18-90 mm	1335 - 2235	Δ = 897
		Average, Excluding Schneider	**Δ = $533**

Auto Iris/Filter Cost (Fixed Focal Length)

• Cosmicar	12-1/2 mm	$130 - $294	Δ = $164
• Cosmicar	16 mm	65 - 260	Δ = 195
• Cosmicar	25 mm	76 - 274	Δ = 198
• Cosmicar	50 mm	78 - 273	Δ = 196
		Average	Δ = $188

Markup: OEM Price/List Price (Kowa) 0.355

Total of Cost Elements $962.00

OEM Quantity Price $341.50

REFERENCES

4-1. Geddis, H.A., et al., "Atmospheric Transmission in the 1 to 14 Micron Region," Proc. Roy. Soc., A206, 87 (1951).

4-2. Hudson, R.D., "Infrared System Engineering," IH5, Wiley Interscience, 1969.

4-3. Houghton, H.E., and Walker, W.R., "The Scattering Cross Section of Water Drops in Visible Light," J. Opt. Soc. Am., 39, 995 (1949).

4-4. Middleton, W.E.K., "Vision Through the Atmosphere," 63, University of Toronto Press, 1952.

4-5. Arnulf, A., et al., "Transmission by Haze and Fog in the Spectral Region 0.35 to 10 Microns," J. Opt. Soc. Am., 47, 491 (1957).

4-6. Atlas, D., et al., "Optical Extinction by Rainfall," J. Meteorology, 10, 486 (1953).

4-7. Biberman, L.M., "Effect of Weather at Hanover, Federal Republic of Germany, on Performance of Electro-Optical Imaging Systems, Part 1," Institute for Defense Analysis HQ76-18660, Aug. 1976.

4-8. Barhydt, H., "Application of Infrared Technology for Aircraft Landing Aids," Air Transport Assoc. of Amer. Symposium on Visibility Enhancement in Poor Weather, May 1969.

4-9. Lloyd, J.M., "Thermal Imaging Systems," Plenum Press, N.Y., 1975.

4-10. Kourtz, P., and Pinson, W.E., Forest Fire Mapping Using 8-13μ Pyroelectric Vidicon, Information Report FF-X-52, Canadian Forestry Institute, Ottawa, Ontario, Canada.

SECTION V

IMAGE PROCESSING HARDWARE TECHNOLOGY SURVEY

INTRODUCTION

This section surveys the state-of-the-art in data processing technology to determine which devices are capable of meeting the WADS requirements. A complete presentation of all the material studied and reviewed is beyond the scope of this report. Therefore, the material is given in abbreviated form with the most important points or conclusions. Those needing more detail are directed to the bibliography given at the end of this section.

Data processing technology is in a state of rapid flux. Even the manufacturers can't agree on just what to call their products. Generally, a microcomputer is an LSI chip or chip set already packaged on a printed circuit board with all the necessary peripheral circuitry, microprogrammed ROM, and enough RAM to make up a complete processing system (see Table 5-1 for definitions of data processing terms). The board can be housed in a chassis capable of accepting additional memory with a power supply and some sort of front panel control. A microprocessor usually means just the basic LSI chip or chip set, but can include peripheral circuitry if mounted on the same printed circuit board. A microcontroller is just a microprocessor with simple architecture and a limited instruction set. All of the 4-bit devices fall into the microcontroller category and are used in low speed applications such as industrial control. Defined in terms of functional capability or complexity, there are four general categories:

(1) General-purpose computation, such as data and message processing, and multitask efforts.

(2) Signal processing for real-time data acquisition and signal analysis.

(3) Dedicated processing such as in data formatting and display, and data acquisition and storage.

(4) Controllers for memory, I/O, and instrumentation.

The semiconductor technology used for these various devices covers the whole spectrum: pMOS, nMOS, CMOS, TTL, TTL/Schottky, I^2L and even ECL. pMOS is limited mostly to the 4-bit devices but also includes some 8-bit machines and the 16-bit processors from National, IMP-16 and PACE. The bipolar technologies are limited almost exclusively to the bit slice devices. The most popular bit length is 8 bits, but the number of 16-bit devices is increasing because of the demand for increased processing speed without the necessity of going to bipolar technology. The 16-bit processors can achieve faster overall instruction times because fewer microcycles are required per instruction.

Table 5-1. Glossary of Data Processing Terms

RAM	Random Access Memory: Any type of memory which has both read and write capability. The current access time is independent of past access times for both read and write operations.
ROM	Read Only Memory: Any type of memory which cannot be rewritten. Data patterns are permanently recorded. Such storage is useful for programs or tables of data that remain fixed and is usually randomly accessible.
CPU	Central Processing Unit: The part of a computer system that controls the interpretation and execution of instructions. It contains the arithmetic/logic unit (ALU) which executes adds, substracts, shifts, AND's, OR's, etc.
FIFO	First-In-First-Out: Refers to a type of memory register that allows data to be stored in a queue. The first entry at one end is the first to be taken out at the other end.
DMA	Direct Memory Access: Refers to a procedure for entering or removing data directly to or from the main memory of a computer without the intervention of the CPU. It is used for high speed transfers where processing is not required.
A/DC	Analog-to-Digital Converter: An electronic device for generating binary equivalents of analog voltages or currents.
PROM	Programmable Read-Only Memory: An integrated circuit array that is manufactured with a pattern of either all logical zeros or ones. The user then writes his specific pattern into the device by selectively changing the pattern with a special hardware programmer.
Stack	A sequence of registers and/or memory locations used in LIFO fashion (last-in-first-out). A stack pointer specifies the last-in entry (or where the next-in entry will go).
OEM	Original Equipment Manufacturer.
Chip	A rough designation for any integrated circuit.
MODEM	Modulator/Demodulator: A device or circuit used in sending digital information over telephone lines.
I/O	Input/Output: Refers to any port or interface of a data processing system or device through which information is passed.

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The conclusion of this study is that, currently, a bipolar microprocessor would be needed for meeting the estimated WADS computation requirements. Although the nMOS processors are presently a little slower than desired, it is virtually certain that in just several years these lower cost nMOS processors will also be adequate for WADS. For the 1980 time period either of the above mentioned microprocessors is expected to meet the WADS computational needs at very low costs. However, the breadboard phase of WADS also requires flexibility for supporting algorithm modifications during field testing. A minicomputer with full software support offers much more breadboard flexibility than the microprocessors. Although the present minicomputers are probably too slow for meeting the "worst case" WADS computation requirements, the better minicomputers are fast enough to support evaluations and field testing of the proposed algorithms. Therefore, it is recommended that a high performance minicomputer be used for data processing in the WADS breadboard.

SELECTION CRITERIA

The general criteria for device selection are presented in Table 5-2. Several factors are listed along with brief comments on their significance. The following criteria were derived from this list based upon consideration of the special requirements related to WADS:

(1) Must meet anticipated speed requirements.

(2) Must have DMA capability.

(3) Must have addressing capability of at least 8K words of memory.

(4) Must be capable of operation in the highway environment.

(5) Must be commercially available.

(6) Software support must be available.

The criteria concerning device speed and direct memory access (DMA) are based on the anticipated data rates from the sensor. The data rate will be high because of the types of sensors being considered and the nature of the parameters to be determined. The requirement for a minimum of 8K words of memory (directly addressable) was based on estimates of algorithm program size and expected buffer requirements. Consideration of the highway environment is required because of the extremes in temperature, and humidity and smog effects are also important. Commercial availability is important from a cost point of view and affects both initial purchase and maintenance.

Software support affects development costs mostly but is also important for maintenance or enhancements to meet future requirements.

A list of the technologies to which these criteria were applied is given in Table 5-3.

Table 5-2. General Microprocessor Selection Criteria

Selection Criteria	System Design Factors
MICROPROCESSOR SUPPLIER	
Reputation, microprocessor availability	Is the microprocessor in production and available in quantities? The longer a product is available, the better the pricing.
Documentation and application notes	Must be adequate to support design.
Software commitment	Proves dedication to microprocessor markets.
Complete microcomputer cards or systems	Flexibility in early hardware and software development.
Pricing and second source	Cost effective with competition.
HARDWARE	
Power supply requirements	Can increase total system cost.
Clock and cycle time	Determines speed and necessary circuit design for clock generator and timing.
Semiconductor technology	Is it a proven process used for other producible products?
Interfacing requirements	TTL or CMOS compatibility or special.
Packaging	Number of packages required impacts PC board costs.
MICROPROCESSOR ARCHITECTURE	
Word length	Makes some applications more efficient.
Addressing capability	Enough memory for present and future.
Registers, ALU, stack instruction set, addressing modes and I/O	All these factors result in program efficiency, which affects amount of memory and execution speed or performance for a particular application.

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Table 5-2 (Contd)

Selection Criteria	System Design Factors
MICROPROCESSOR SYSTEM	
Bus control capability	Amount of external logic necessary to efficiently control peripheral devices.
Direct memory access	Needed to support high speed I/O devices.
Interrupts	Necessary in real-time applications or for more efficient I/O.
Compatible functions Memory Buffers Clock generators Input/output Communications interface	Can provide for easily assembled minimum systems or medium sized systems with fewer discrete logic functions for bus control and buffering.
MICROPROCESSOR SOFTWARE	
Stand-alone assemble, editor, debug monitor	Useful in microcomputer development system during early design phases.
Cross assembler for batch and time-sharing	Timeshare only feasible on small project. Batch assembler on minicomputer or larger system is very effective.
Software documentation	Required for a good start; macro-assembler very useful.
Simulator	Good start up, too; good only for small effort.
Higher level language	Possible documentation and productivity benefits, assembly language dominates.

Table 5-3. Processor Technology List

The following microprocessors were considered for the WADS application:

8-bit types:

Fairchild F8
F8-1 (3859)

Intel 8008-1
8080A
8085

Electronic Arrays EA9002
3870

MOS Technology 6502A
5065

Motorola 6800

National SC/MP

RCA COSMAC (1802)

Rockwell PPS-8

Signetics 2650

Zilog Z80

16-bit types:

National IMP-16
PACE

Texas Instruments TMS9900

Data General mN601

General Instrument CP1600

Western Digital MCP1600

RCA ATMAC

Bit-slice types:

AMD 2900

Fairchild MACROLOGIC
9440

Table 5-3 (Contd)

Intel 3000

MMI 6700

Texas Instruments 74S481
SPP0400

Motorola 10800

The following microcomputers were considered for the WADS application:

DEC LSI-11

Data General micro NOVA

Plessey MIPROC-16

ITEK ATAC-16M

Signetics 8 x 300

The following minicomputers were considered for the WADS application:

DEC PDP-11/03

Data General NOVA series

Hewlett-Packard 21MX series

Varian V77 series

Computer Automation LSI-2 series

DESCRIPTION OF TECHNOLOGY

Features

A general way of categorizing the capabilities of the various LSI devices is shown in Figure 5-1. Devices of characteristic word lengths are distributed according to functional capability. The functional capability of a device or set of devices is mainly determined by three factors:

(1) Internal architecture.

(2) I/O capability.

(3) Instruction set.

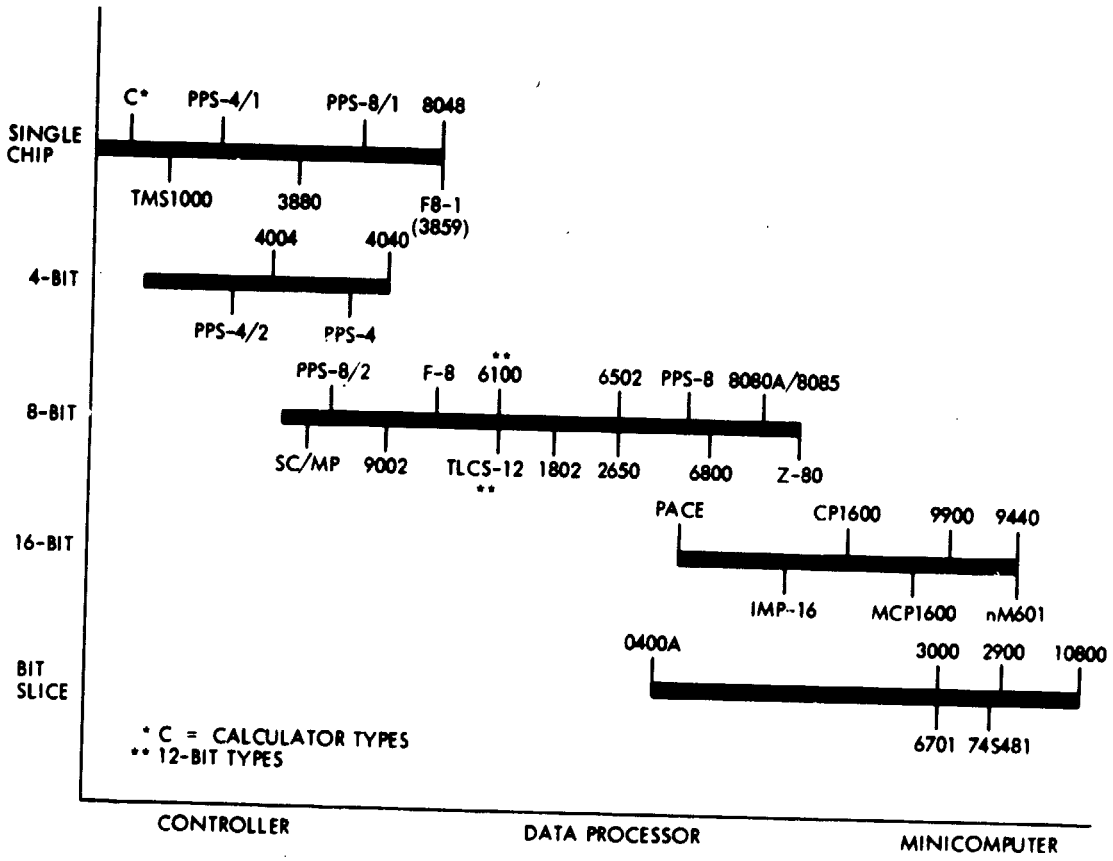

Figure 5-1. LSI Device Categories

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Many trade-offs have been made in the design of the various types of data processing devices and systems. In examining them for applicability to WADS, it is not sufficient to look only at instruction cycle time and memory access time. Certain types of architecture will be more efficient in doing the WADS tasks. Ideally, bench mark programs would be run on each type, and a comparison would be made of execution times, efficient use of memory, etc. To illustrate some of the major differences available, three examples will be presented.

The first device is the IMP-16. Its basic architecture is shown in Figure 5-2 (without I/O). It has a typical stack architecture, used by many manufacturers, with a LIFO stack and working registers as part of the CPU. Address and data buses are multiplexed to reduce pin requirements. This type is good for many general purpose applications with a mix of data manipulation and arithmetic. Among the 8-bit devices, the popular 8080A uses this type with the exception that program and data spaces, the LIFO stacks, are found in external memory (RAM).

A new type of architecture is used by the second example, the TMS 9900 (Figure 5-3). This approach puts not only program and data spaces in external memory but all the general purpose registers as well. The memory-to-memory architecture that results allows very flexible programming and has the following advantages:

(1) The number of workspace register files is not fixed.

(2) Interrupt handling is fast and efficient because all data used in program execution is contained in memory.

(3) Separate data, address, I/O, interrupt and control bus structures eliminate the need for many external devices such as bus multiplexers (IMP-16).

(4) Regular I/O and DMA interfaces are simplified (both in hardware and software).

This type of architecture appears to be suitable to the WADS application. In addition, an I^2L version of this device set, the SBP9900, has just been announced. It needs only a single phase clock, operates from one +5 volt power supply, is fully TTL compatible, and has the full temperature range of -55° to $125^{o}C$.

The third example is the MIPROC-16. This device, shown in Figure 5-4, was designed as a very fast, dedicated data processor/controller. The semiconductor technology used is a combination of standard and custom TTL (mostly MSI Schottky). Indexing and interrupts can be added, as options, to the basic system. Note that program memory and data memory are on separate buses. This allows parallel fetch and execution in a single instruction cycle. Most of the processors instructions are done in one 350-nanosecond cycle. I/O is also simple and fast because it is similar to a data memory access.

A comparison of some general microprocessor features is presented in Table 5-4. The MIPROC-16 just discussed probably fits best into the bit slice category even though it is not really this type.

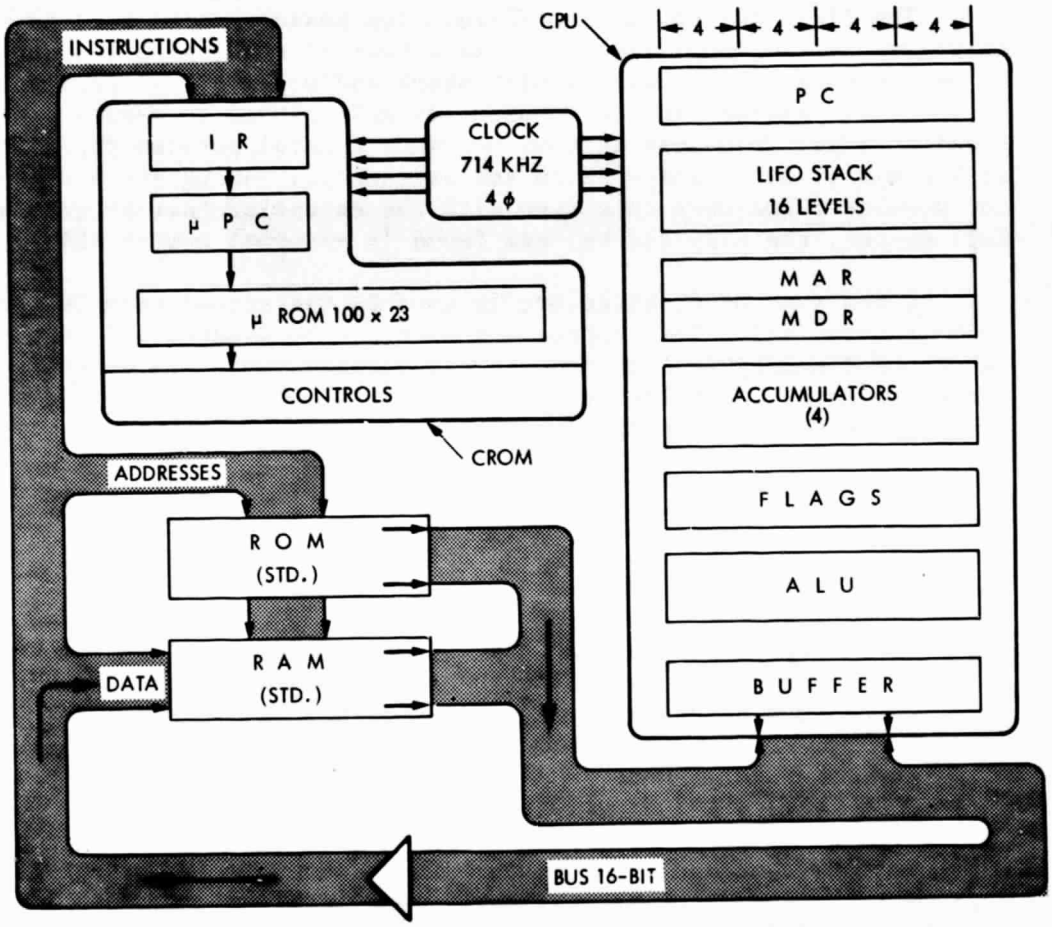

Figure 5-2. IMP-16 Microprocessor Architecture

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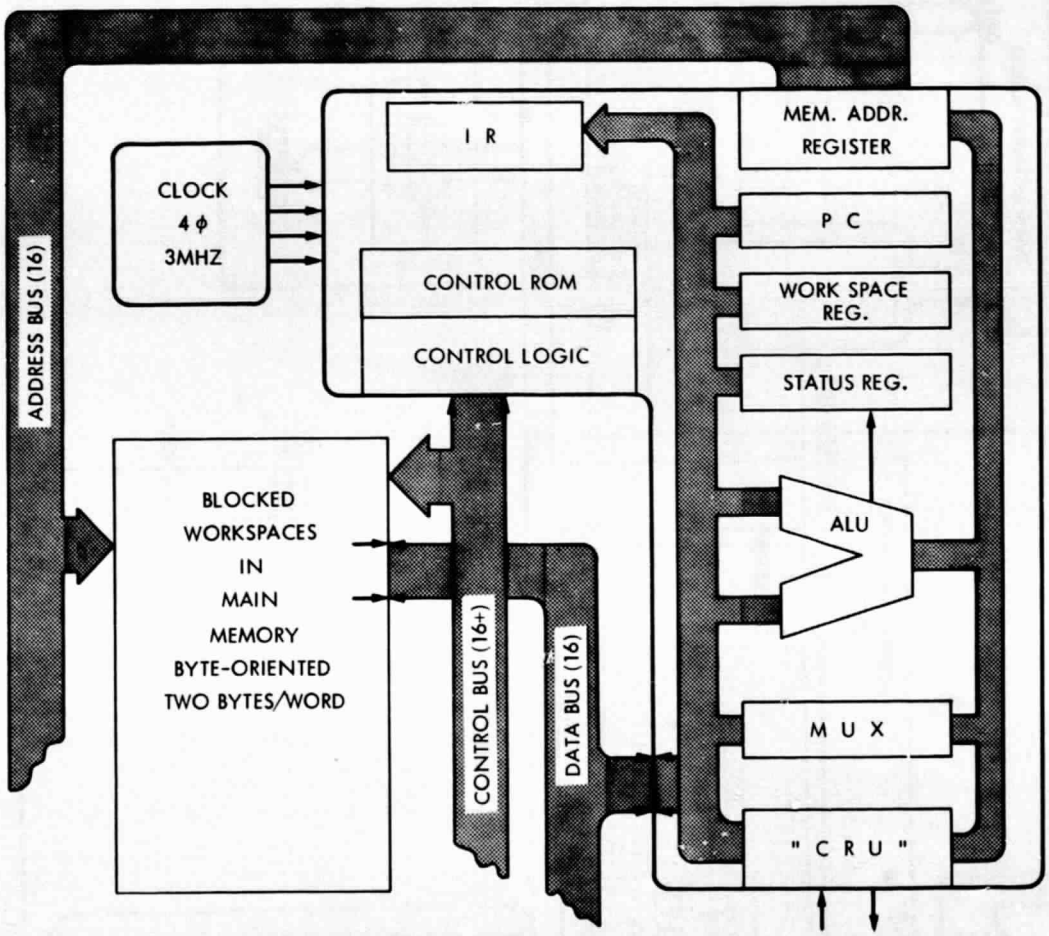

Figure 5-3. TMS 9900 Microprocessor Architecture

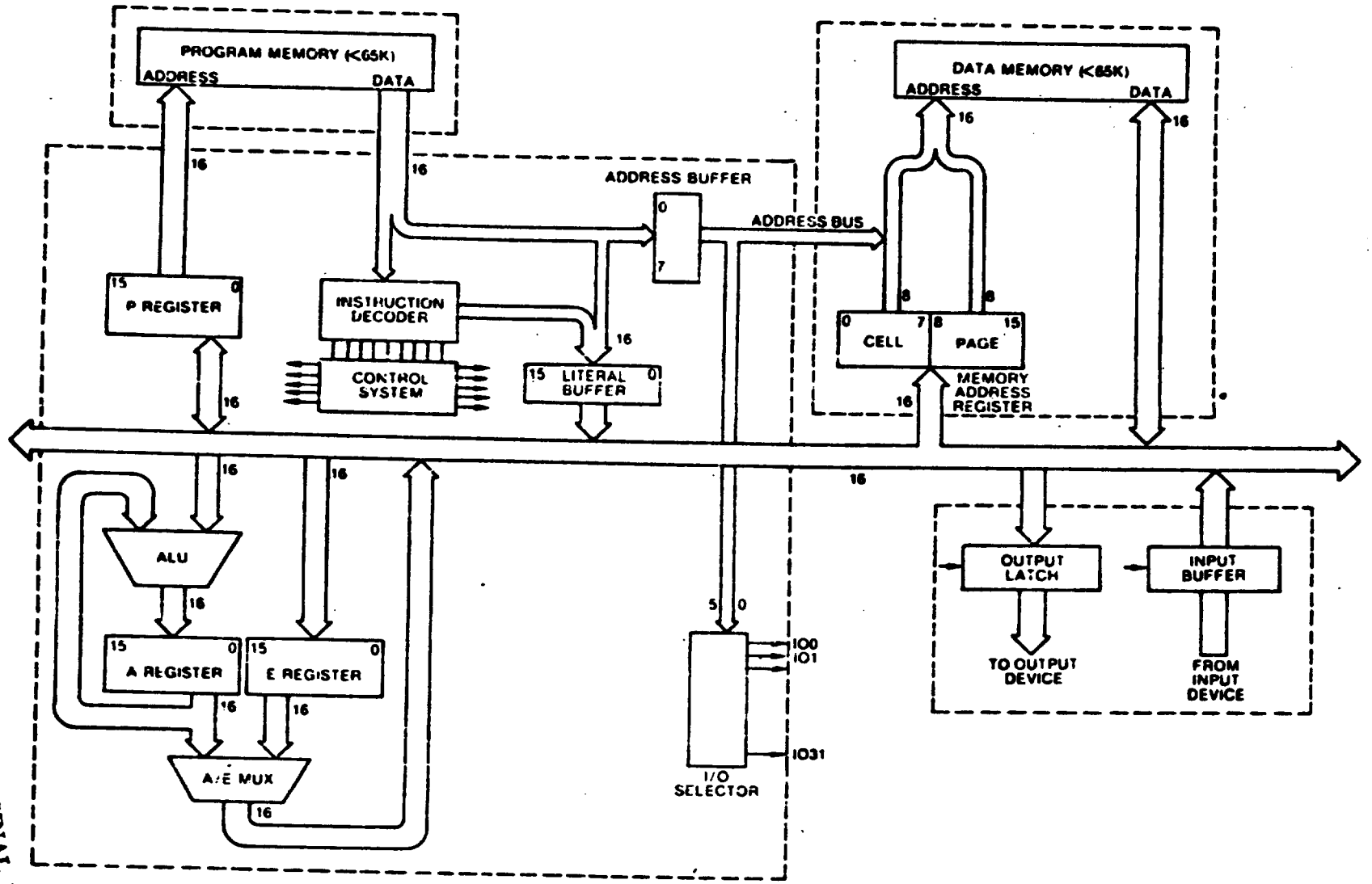

Figure 5-4. MIPROC 16 Microcomputer Architecture

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Table 5-4. Comparison of Microprocessor Features

	T^2L Equiv.	Typical Memory (K words)	Program Size	Interrupt Channels	Maximum Execute Time (μs)	Number of Pkgs.
General Purpose	100 & up	4-64	30-150	5-10	4-8	10-50
Dedicated	100 & down	2-4	50	Up to 5	5-10	5-10
Controller	50 & down	1-2	50 & down	2 or so	5-10	Below 5
Calculator (custom)	25	None (Generally)	25 & down	1 or 2	100 or so	1 or 2
Bit-Slice	100-200 & up	64		5-10	5	50-100

Future Developments

The following predictions are made for the near future (2 to 3 years) as manufacturers continue to improve on older technologies and expand on several promising new developments. There will be faster and more dense MOS which will continue to improve the speed of memories as well as their size (bits per chip) and the cost per bit. This is good for WADS because considerable memory will be needed to store digitized video data. Sixty-four thousand bit MOS memory chips should be "off-the shelf" for 0.05 cent per bit or less. More devices using integrated injection logic (I^2L) will be commercially available. This newly developed bipolar technology promises high speed at low power while still allowing the high density needed for microprocessor design.

Another technology that can deliver high speed at low power is CMOS/SOS (complementary MOS on sapphire). It was announced several years ago but has been quite slow to reach the commercial market in production quantities. However, the continued efforts of several companies are now beginning to bear fruit. The RCA ATMAC microprocessor listed earlier uses this technology. This is a 16-bit device, and more 16-bit devices in all the technologies are predicted as a trend toward more processing power.

To make their products more useful (and thus more salable), vendors will also continue to improve the software and documentation for their microprocessors. This will help lower development cost for a WADS and may add processing capability that will help make algorithm programs simpler and faster. Another future development that may reduce algorithm processing time is the availability of special, high-speed function devices that may allow preprocessing of image data at the

sensor/processor interface. The commercial demand for such devices as correlators for application to radar and sonar data processing already exists and devices to meet the need are beginning to appear. This trend will continue.

WADS APPLICATION SUITABILITY

The following factors were considered in analyzing the suitability of various data processors for the WADS.

(1) Highway environment.

(2) Reliability.

(3) Cost.

(4) Flexibility.

Highway Environment

Three things in the highway environment will affect data processing electronics the most. These are temperature, humidity, and contamination.

Currently available temperature ranges are as follows:

(1) MOS: 0° to $70^{\circ}C$

(2) CMOS/SOS: -55° to $125^{\circ}C$

(3) Bipolar: -55° to $125^{\circ}C$

Wider ranges for MOS are expected in the future. For example, Motorola has announced a new chip set for the 6800 microprocessor that has an operating temperature range of -40° to $85^{\circ}C$. Though not quite as broad as the MIL-STD-883 temperature specifications, this range is probably adequate for WADS. Both CMOS/SOS and bipolar technologies are available in the wide temperature range, but the cost is considerably higher.

The effects of humidity and contamination can be controlled by the standard methods used in high reliability applications. Circuit boards are coated with Solathane or a similar compound, packaging is done in a way that minimizes the number of interconnections between modules, and connectors that make good, gas-tight connections are used. All electronic modules are then put in some overall enclosure.

Reliability

Reliability is closely related to the factors just mentioned. Operation in the highway environment will definitely have an adverse effect on reliability that can only be minimized by careful design

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considerations. A brief summary of factors affecting reliability is given below:

(1) Solid state devices are inherently reliable after some "burn-in" or "infant mortality" period.

(2) This reliability is enhanced in simple, standard ways such as:

(a) Cooling to stay well within temperature specification limits.

(b) Encapsulation to eliminate moisture and contamination from direct contact with components and printed circuit boards.

(c) Protective circuitry may be added to eliminate excessive currents and voltages and increase fault tolerance.

(d) Shielding may be included to guard against noise.

(e) Thoughtful design will include the use of standby or limited operating modes to allow for "graceful degradation" instead of catastrophic failure.

(3) If momentary failures in hardware operation do occur that affect programs or data, some recovery mechanism must be available that will allow resetting to some known state.

A good way of ensuring that the type of recovery described in (3) can be accomplished is to store all the programs in ROMS where they cannot be altered except by a device failure.

Cost

A summary of current costs for the types of hardware discussed in this section is shown in Table 5-5. Note that an A/D converter and a sample-and-hold were also included. This type of device would be part of the interface between the sensor and the processor. Both are included here because they may be a significant cost factor in the final package.

Flexibility

Because the technology is changing rapidly and the final design of the WADS will not be known, even after the conceptual design phase, hardware choices that maximize flexibility are quite important.

Table 5-5. Current Hardware Cost

Type	Dollars
Chip sets	20-200
Microprocessor-on-a-board (with some memory)	300-1,000
Bit-slice controller/processor	500-1,200
Minicomputer-on-a-board - no RAM	1,500-2,500
Minicomputer packaged with 8K-32K	4,000-10,000
Video rate A/D converter	800-1,000
Video rate sample-and-hold	100-200

Processing Hardware

To discuss the choices of processing hardware as they directly affect applicability to the WADS, four 'scenarios' are proposed.

The first possibility is to choose a minicomputer that has a corresponding microcomputer which uses the same software. The advantages and disadvantages of this approach are summarized in Table 5-6. Three

Table 5-6. Compatible Minicomputer/Microcomputer

Advantages:

(1) Can use already developed software.

(2) Can lease peripherals and do algorithm software on minicomputer.

(3) Software easily transferred to field design.

(4) Can keep minicomputer and use for further software development or reconfigure for other uses.

Disadvantages:

(1) If field requirements and algorithm design are too stringent, scrap work and start over.

(2) Choosing minicomputer automatically chooses microcomputer or very close alternate.

(3) All current designs use MOS - bipolar not quite here.

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or four such combinations are presently available. In several cases, there are some software differences (as with the PDP-11/LSI-11), but translation from one to another should not be difficult. The big question is: "Will the microprocessor now available be able to handle the WADS algorithms and data rates?"

The second possibility is to use a board level computer/controller that can do high speed processing. The same device would be used for both breadboard and final design (perhaps with some modifications in packaging). The advantages and disadvantages of this approach are summarized in Table 5-7. The main problem with this approach is that there is only one such device presently available (MIPROC-16), and it has some serious drawbacks.

The third scenario is closely related to the second. It is to build a custom special purpose processor with bit-slice devices (such as the AMD 2900 series). The advantages and disadvantages of this approach are summarized in Table 5-8. The firmware/software effort required for this would be quite expensive - especially without firm specifications of the required performance. Some flexibility would have to be maintained throughout breadboard development.

Table 5-7. Board Level Computer/Controller (Bipolar)

Advantages:

(1) High speed.

(2) Wide temperature range.

(3) Packaged hardware with at least minimum software.

Disadvantages:

(1) Limited software.

(2) Cross-assembler must be purchased, installed, and learned (probably FORTRAN).

(3) Development systems available seem awkward and expensive.

(4) End product may be locked into one vendor.

(5) If concept is not feasible, hardware will probably be a total loss.

(6) Bipolar memories are presently more expensive.

Table 5-8. Custom Bit-Slice Processor

Advantages:

(1) Tailored instruction set.

(2) Architecture optimized for interfaces.

(3) Technology has wide temperature range.

(4) High speed processing.

(5) Microprogramming can be used.

Disadvantages:

(1) Extended development schedule - high cost.

(2) If concept not practical, work is wasted.

(3) Bipolar memories are presently more expensive.

The last scenario to be discussed here is that of using a high-performance minicomputer for the breadboard and testing the WADS concept in the field before any commitment to a 'final' design. The advantages and disadvantages of this approach are summarized in Table 5-9. This seems to allow the most flexibility and be the most cost-effective. At least one high-performance minicomputer that employs bit-slice technology is already on the market (Varian V-77). If the WADS concept is successfully demonstrated with the breadboard and high speed processing remains a requirement, a viable field design could probably be derived from such a minicomputer and further development costs would be minimized.

The mainstream of microprocessor development is still centered in MOS technology. Many improvements have been made in MOS (such as going from pMOS to nMOS, use of ion implantation, etc.) that have enhanced performance. It is most likely that a nMOS processor will be able to do the WADS tasks by the time a commitment to 'final' design must be made.

PERFORMANCE COMPARISON

Performance Parameters

As mentioned earlier, the comparison of performance parameters and the determination of applicability is very difficult. Important parameters are sometimes not reported on vendor data sheets. Also, devices may be characterized in such a way as to be not directly comparable with

Table 5-9. Minicomputer for Breadboard

Advantages:

(1) Least development effort - and cost.

(2) Takes full advantage of developed software.

(3) Can be easily reconfigured to other tasks.

(4) Changes easy to make in the field.

(5) Can lease peripherals and do all assembly on same machine.

(6) If concept fails in the field, minimum loss.

(7) May take best advantage of developing technology.

(8) May use microprogramming - most machines.

Disadvantages:

(1) If field model is not compatible:

(a) New software.

(b) At least partial redesign of front end interface.

(c) Redesign readout and communications interfaces.

(2) May obscure some field design problems.

another vendor's information. Table 5-10 lists some of the more important parameters used in trying to compare the various processors. Some of the items may better be called features, but they all have a direct bearing on operational performance or efficiency in doing development and software changes.

Performance Comparison

The chart in Table 5-11 is an attempt to show a comparison of the various parameters for some of the most promising processors currently available. Blanks are used where information was not available or not applicable. The 8080A was included as a reference point for those familiar with 8-bit microprocessor technology. As an example of how misleading it can be to compare numbers, consider the memory access time of the 8080A and the MIPROC-16 (the difference in word lengths is irrelevant). For the 8080A, the 340 nanoseconds is the minimum time it will take to access a particular address (not a complete fetch cycle).

Table 5-10. Processor Performance Parameters

Processing and I/O Time:

(1) Add time.

(2) Multiply/divide time.

(3) DMA cycle.

(4) Memory access.

Architecture:

(1) Microprogramming.

(2) Controller/data processor.

Software:

(1) Completeness.

(2) Cross-assembler.

(3) Development system.

For the MIPROC-16, the 350 nanoseconds is the minimum time for a complete memory cycle including instruction execution. Such an instruction might be "Add the contents of memory location M to the contents of the accumulator A." The 8080A would take 1.33 microseconds to do the same type of instruction. Another example from the table that needs some explanation is from the same column but for the LSI-11 and the Micronova. These machines use an instruction called MOV. This means move a word of information from a source to a destination. Thus, to bring the contents of a memory location into an accumulator (general registers may be used as accumulators) requires 3500 nanoseconds. To find instruction times in the LSI-11, it is necessary to take into account a Basic Time, a Source Address Time, and a Destination Address Time. Basic Time is the sum of Fetch Time, Decode Time, and Execute Time. Source and Destination Time can be quite different from any one of seven modes of operation.

From the above examples, it should be clear that detailed performance evaluations or comparisons are not easy to make. Of course, at this stage, we are not really trying to make a decision between two machines as similar as the LSI-11 and the Micronova. Preliminary work on the detection algorithms has produced estimates for the number of computations required. These are given in Table 5-12. The time needed by each of five processors to do these computations is illustrated in Figure 5-5. Because the algorithms are not yet developed, these times are based strictly on raw execution times. The time required for buffering, counting, testing, and other data manipulation is not included. A

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Table 5-11. Processor Performance Data

Processor	Add Time (μsec)	Multiply/ Divide	DMA Cycle	Memory Access (ns)	Microprogram	Cont./ Proc.	Completeness*	Cross- Assembler	Develop. Syst.*
8080A-1	1.33	-	2000	340	No	P	10	Yes	10
IMP-16	4.6	-	1000	1400	Yes	P	10	Yes	8
TMS 9900	2.7	17.5/-	-	-	No	P	8	Yes	9
ATMAC	0.35	0.7/-	700	<200	No	P	3	Yes	No
LSI-11	2.4	64/78	-	MOV (3500)	No	P	10	Yes	9
Micronova	2.4	41/59	-	MOV (2880)	No	P	9	Yes	9
Miproc-16	0.35	5.6/11.2	Yes	350	No	C/P	7	Yes	8
8 x 300	0.25	-	Yes	250	No	C	5	Yes	6
21 MX-E	0.91	6.0/9.5	DPC 1620	110	Yes	P	10	No	
2900	0.25	5.1/-	-	-	Yes	-	-	-	-
3000	0.165	-	-	-	Yes	-	-	-	-
SBP 400	1.0	-	-	-	Yes	-	-	-	-
V77-400	1.32	4.9/8	DPC 670	660/330	Yes	P	7	No	-

*0 = minimum, 10 = maximum

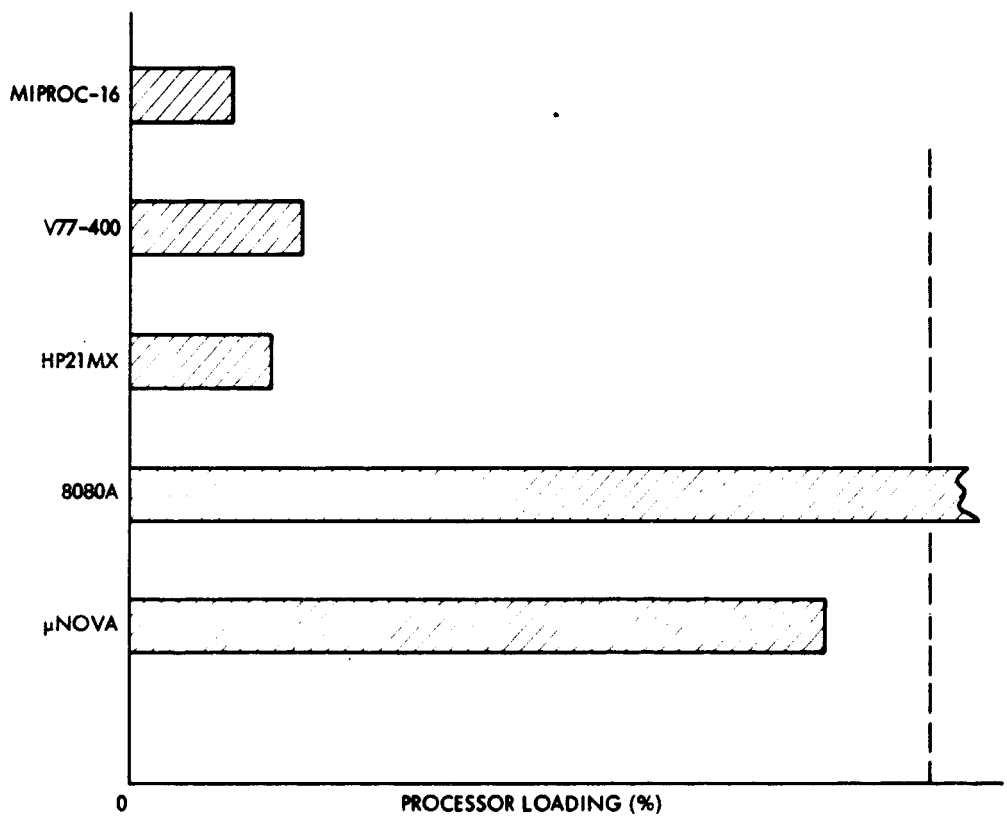

Figure 5-5. Processor Loading

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Table 5-12. Arithmetic Tasks for Algorithm

Additions	130,000/sec
Multiplications	5,000/sec
Divisions	2,500/sec
Table look-ups	60,000/sec

reasonable assumption, based on experience, is that this raw computation time should not exceed one-third of the total interval. Again, the 8080A is included only as a reference point.

The bit slice devices cannot easily be included in this type of comparison. However, the V77-400 which uses the 2900 series bit-slice devices is representative. A custom design would run even faster. This is because the instruction set could be tailored to suit the types of operations required by the WADS algorithms. Obviously, the Micronova cannot handle the basic arithmetic processing task with enough margin for other work. The TMS9900 would also fall short even though it could do the raw computations at a loading of approximately 70%.

The only machines left whose percentage of computation time is reasonable are the high performance minicomputers and a dedicated processor/controller (MIPROC-16).

CONCLUSIONS

Based on the preceding discussions, it is desirable to use a high speed minicomputer for the WADS breadboard, because it is adequate for testing the WADS feasibility and it increases testing flexibility. However, the final production WADS is expected to be a custom-designed microprocessor, since this approach will provide more computation power at a lower cost.

BIBLIOGRAPHY

Proceedings of the IEEE, Special Issue on Microprocessor Technology and Applications, Vol. 64, Number 6, June 1976.

An Introduction to Microcomputers, Volume I, Basic Concepts, Adam Osborne and Associates, 1976.

An Introduction to Microcomputers, Volume II, Some Real Products, Adam Osborne and Associates, 1976.

Microcomputer Applications, Proceedings of Technical Session 1, WESCON 1976.

High Performance Building Blocks for Microprogrammed Systems, Proceedings of Technical Session 26, WESCON 1976.

Single-Board Computers: The Emerging Micro vs. Mini Battle, Proceedings of Technical Session 31, WESCON 1976.

LSI-11, PDP-11/03 Processor Handbook, Digital Equipment Corporation, 1975.

Computer Dictionary & Handbook, Charles J. Sippl and Charles P. Sippl, Howard Sams & Co., Inc., 2nd Edition, 1972.

Predicting Integrated Circuit Reliability Via Failure Mechanisms, D.I. Troxel and B. Tiger, Proceedings of the 1968 Annual Symposium on Reliability, January 1968.

Various current trade magazines such as Electronics, Electronic Design, EDN, Computer Design, Mini-Micro Systems, and Datamation were also used.

Various product literature obtained directly from vendors.

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SECTION VI

IMAGE PROCESSING ALGORITHM TECHNOLOGY SURVEY

A wide range of general processing techniques are applicable to WADS. Examples of these techniques are feature extraction, edge detection, adaptive learning, sequential detection and estimation, and correlation tracking. Excellent surveys and bibliographies are given in Refs. 6-1 and 6-2. The above processing technologies provide only a theoretical basis for developing an algorithm. In practical applications the specific use of these processing methods is very problem-dependent.

SENSOR SELECTION AND SIGNAL DESIGN

The specific sensor selected for WADS will have great impact on the processing algorithm requirements. The algorithm is greatly simplified if the sensor can provide the desired information in a signal of minimized ambiguity. An imaging sensor has the inherent advantage of being able to provide a measure of spatial, spectral, and temporal characteristics of a wide area of the highway. It provides a signal which directly enables manual incident verification; however, the signal does require considerable processing in order to extract the traffic flow parameter data. The processing requirements are affected by the sensor's spatial, spectral, and temporal resolution, and also by the variability of the signatures of the vehicles and the background around them.

Of all the imaging sensors previously surveyed in Section IV, the standard television visual imaging sensor (EIA standard RS-170) was shown to be lowest in cost. The discussions in this section conclude that the spatial and temporal resolutions of the standard television sensors are adequate from a data processing standpoint. The infrared television sensors would provide a slightly more distinct signature for vehicles and slightly better visibility in bad weather. The current cost of these sensors, however, outweighs their small advantages for image processing. Therefore, a standard television sensor is an appropriate sensor from an algorithm viewpoint; however, where possible, the algorithm should be designed to also accomodate infrared television sensors which may become low enough in cost in the future.

The key processing problems for WADS are, in fact, common to all of the imaging sensors surveyed in the previous section. The vehicles which are being detected are highly variable in size and reflectance, and the background around the vehicles is also highly variable. For instance, the signatures of background and vehicles change drastically with respect to (1) different vehicles, (2) different locations, (3) different times of day and night, and (4) different weather conditions. Another difficulty is the complex view geometry of the WADS sensor.

Ideally for the algorithm, the sensor should be located hundreds of feet high with a nearly straight-down view of the highway. In practice, however, sensors will typically be mounted between 25 and 50 feet (7.62 and 15.24 meters) above the roadway. At these heights the sensor's view will result in a very nonuniform resolution and considerable occultation of vehicles by other vehicles.

The above circumstances make the WADS algorithm a difficult problem; they will set limits to what can be determined automatically from an imaging sensor. Furthermore, the WADS processor will need to determine traffic parameters from the image data in real time, which means the algorithms will be severely constrained in allowed computation.

APPLICABILITY OF EXISTING ALGORITHM TECHNOLOGY TO WADS

No off-the-shelf algorithm exists which can be applied directly to the WADS task. As noted earlier, there are many algorithms for applications which are similar in a general sense, but there are none which directly address all of the above-noted specific algorithm difficulties associated with WADS. Therefore, the WADS algorithm will draw upon existing techniques for the general approaches, but the specifics of the algorithm will have to be specially developed for WADS. Examples of algorithm techniques related to the WADS problem are aerial photographic analysis, image analysis for robotics, military detection and tracking with radar and sonar, and real-time tracking and displacement measurements from simple images.

Discussion of algorithms for automatic interpretation of traffic data from aerial photographs is contained in Refs. 6-3, 6-4, and 6-5. These algorithms are not applicable to WADS, because they are not real-time, they require some human interaction, and they do not deal with the same complexities of view geometry. There are sophisticated algorithms being developed for object identification and tracking as part of robotics research (e.g., Refs. 6-6 and 6-7). These algorithms are aimed toward a much broader application than is necessary for WADS, and they currently require substantial human interaction, non-real-time operation, and expensive hardware.

The military uses real-time processing algorithms for detection and processing, but these applications generally involve radar and sonar signals. In some cases simple change detection of image data is accomplished in real-time. We were unable to find any existing military image algorithm applications with requirements similar to those of WADS. Furthermore, the existing algorithms for military applications require hardware implementation costs far beyond the range of costs feasible for WADS.

There are some low cost commercial products which use image sensors and processors for applications analogous to WADS. An example of a commercial device which comes closest to being applicable to WADS is the Perceptoscope by Hamamatsu Corporation. This device costs about

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$12,000, and consists of a television camera, an 8080-based processor, and a monitor display. The image is first level-sliced into black and white via an operater-selected threshold. The operator then defines a rectangular window within the image for which the region of black or white area, width, and centroid can be calculated and tracked on a per frame basis. Such a device can be useful for automatic monitoring of assembly lines; however, it is still substantially inadequate for WADS because it requires operator interaction and is applicable only to simple images which are well defined in terms of thresholding the image into black and white.

The WADS requirements press the capability of current algorithm technology. Current technology is either not real-time, too simple in function, or too expensive. The WADS algorithm basically requires high speed computation, moderate complexity, and low cost. A qualitative summary of performance versus cost for a WADS algorithm and various current image processing algorithms is depicted in Figure 6-1. It is primarily the rapidly increasing computation speed per unit cost of processing hardware technology which now makes a WADS algorithm feasible.

FEATURE EXTRACTION TECHNIQUES

A standard television camera acquires about 240 active scan lines 60 times a second. If each of these lines were sampled and digitized 300 times, there would be over 4 million samples per second. Clearly, a low cost processor cannot deal with this volume of samples, nor is there a need to analyze all the samples in order to determine traffic parameters. Feature extraction is the technique of selecting a reduced representation of the total data which still contains the information desired. Obvious examples of features for the WADS would be the set of features from lines across the highway lanes, or along the center of the lanes.

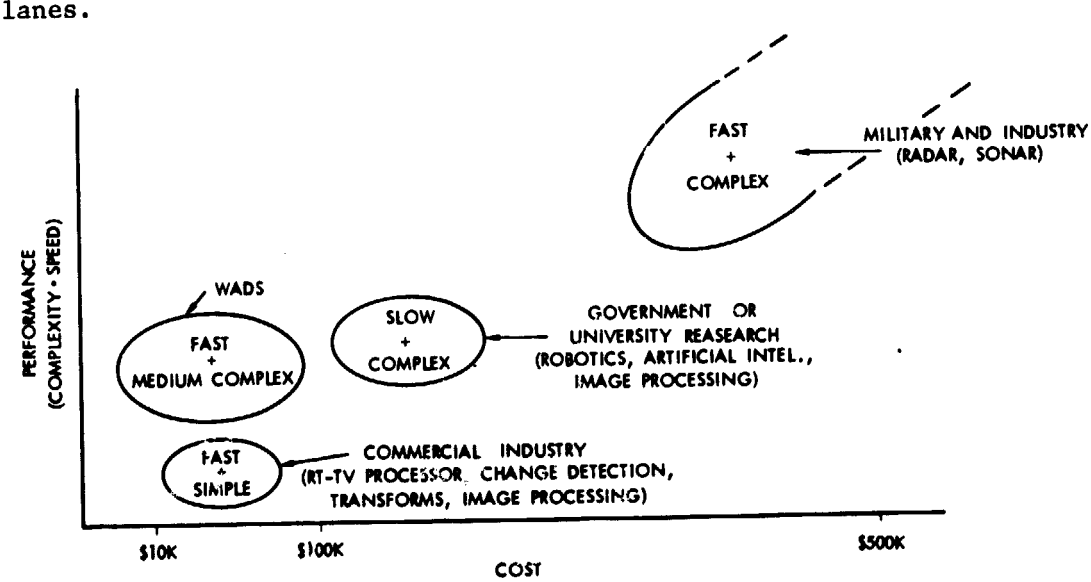

Figure 6-1. Summary of Performance Vs. Cost of Various Image Processing Algorithms

A line across the lanes is an excellent feature in that one single line is all that is needed to detect the passage of any vehicle, since any vehicle moving along the highway must pass through the line. Alternately, a line along the center of a lane could miss vehicles changing lanes, small vehicles such as motorcycles, or headlights and taillights, which are the only visible parts of the vehicles at night. On the other hand, a cross-lane line is a poor feature for measuring the location of the vehicle in the along-lane direction. This is because the cross-lane line basically detects presence or not of the vehicle over a one-thirtieth of a second interval, thus resulting in an along-lane position uncertainty corresponding to the movement of the vehicle in a thirtieth of a second. For example, the use of two cross-lane lines to measure velocity would result in a time interval uncertainty of one-fifteenth of a second. Thus, to achieve a 5 percent accuracy in measuring speed, the time interval between line crossings by the vehicle must be 1.33 seconds or greater. For a vehicle traveling at 100 feet per second (30.5 meters per second), the spacing between the cross lanes would need to be at least 133.3 feet (40.6 meters).

An along-lane line, however, is an excellent feature for measuring location of the vehicle along the lane, since this feature basically defines where the vehicle is at each one-thirtieth of a second (every one-sixtieth of a second if both fields of each frame are used). For example, an along-lane line defines the position of the vehicle with an uncertainty of about one picture element. Even less uncertainty is possible, as is discussed in Ref. 6-8. The near-field resolution of the camera can be better than 0.25 feet (7.62 cm) of highway per picture element. Therefore, the uncertainty in position is about 0.25 feet (7.62 cm), and the vehicle's speed can be measured to within 5 percent accuracy when the vehicle has moved as little as 10 feet (3 meters) regardless of the vehicle's speed.

The above discussions indicate that a combination of a cross-lane line and along-lane line would provide a very good set of features for the WADS. A cross-lane line feature should be used to detect the presence of any vehicle passing along the highway, and to also indicate where the vehicle is in the cross-lane direction. The along-lane line feature need only be taken when the cross-lane line has indicated a vehicle is passing, and then only an along-lane line segment in the vicinity of the vehicle needs to be taken. A sequence of these along-lane line features from successive frames then provides the information desired for measuring location and speed of the vehicle.

SAMPLING RATE CONSIDERATIONS

The sampling rate of standard television cameras is 60 fields per second with two fields being interlaced into a frame 30 times per second. This sampling rate was specifically derived to be near to the minimum acceptable for general human viewing of moving objects. Therefore, it is obvious that this sampling rate is at least adequate for the

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real-time imaging sensor in the incident-verification operating mode. Furthermore, the use of slower, or faster sampling rate image sensors would entail the use of nonstandard cameras and monitors, which would result in higher costs. Thus there is little interest in assessing whether the algorithm acquiring traffic parameters from the image can operate at sampling rates below 30 per second. The primary question is whether the 30 samples per second rate is adequate.

The primary requirement for sampling rate is that it be high enough for the cross-lane line feature to adequately detect passing vehicles. One must remember that vehicles include small motorcycles and headlights and taillights. These may subtend only several picture elements in the image. At the same time, a vehicle may be traveling as fast as 100 feet (30.5 meters) per second or 3.3 feet (1 meter) per frame, which can amount to as much as 10 picture elements of motion per frame. There is some concern that a vehicle signature of only a few picture elements which moves 10 picture elements per frame may be undetected by the cross-lane line feature. However, note that each picture element of a television sensor obtains its intensity measure as the result of integrating the light energy over the full interval of the one-thirtieth of a second. Thus an object one picture element in size which passes completely through the cross-lane line feature during the frame interval still influences the measured average intensity of the samples from the line feature. However, the influence of the passing vehicle on the average measured intensity is reduced by the fraction of time during the frame in which the vehicle was not subtended by the line feature. The only vehicle signatures as small as a few picture elements are headlights and taillights, but these signatures are generally very bright compared to their surroundings and are therefore readily detectable by a cross-lane line sampled 30 times per second. Consequently, it is anticipated that the sampling rate of standard television cameras will be adequate for obtaining traffic parameters.

The above discussion indicated that the sampling rate of standard television cameras is adequate for incident verification and traffic parameter measurements. Furthermore, it was observed that lowering the sampling rate would not result in reducing the image sensor costs. If a lower sampling rate were desired, the standard television camera is still the best choice from a cost standpoint, and the lower sampling rate can be achieved by subsampling. The key cost issue with respect to sampling rate is, in fact, associated with the cost of communicating the image data for incident verification. If incident verification actually requires 30 frames per second, then a large initial cost is generally incurred to establish microwave or cable transmission of the video data between the observation points and the traffic operations center. On the other hand, if data compression is used and a lower frame rate (e.g., one frame per 5 seconds) is adequate for incident verification, then this image data could be very inexpensively transmitted over standard phone lines. It is conceivable that a single television frame would be adequate for actual incident verification, in which case the only

concern is over the frame rate required to properly operate a pan/tilt/zoom mechanism for the camera during the period an operator is accurately locating the incident. At this point, it is felt that one frame per 5 seconds would be adequate, especially if the operator were given computer interactive assistance (e.g., ability to define the view of the next frame via a light pen). Only experimental testing can determine whether this approach could provide a useful cost saving alternative.

RESOLUTION CONSIDERATIONS

Once again it is noted that there are large cost advantages to using the mass-produced standard television sensors, monitors, and other associated hardware. Therefore, the key issue is whether standard television resolution is adequate for WADS.

The standard TV camera has 525 scan lines per frame. Owing to vertical retrace time, only 480 of these lines are useful. Furthermore, the 480 lines consist of two consecutive 240-line fields which are interlaced and offset in time from one another by one sixtieth of a second. The resolution of a television camera is often specified in terms of the number of lines of an image which can be resolved per field of view. A good quality analog scanning camera can provide vertical resolution of about 350 lines (degraded from 480 by analog scanning inaccuracies); solid-state sensors such as charge-coupled devices will ultimately be able to provide close to 480 lines resolution. A vertical resolution of about 240 lines is obtainable from either type of sensor by using only one of the fields. A good quality analog scanning camera can provide horizontal resolution of 640 lines, and solid-state sensors are also inherently capable of providing this resolution. Observe that 640 lines of horizontal resolution and 480 lines of vertical resolution result in equal horizontal and vertical image resolution since the horizontal field-of-view for the camera is 4/3 as large as the vertical field of view.

The basic reolution of the standard camera is either 480 lines, or 240 lines. Higher resolution cameras with more scan lines per frame are readily available, but they are more costly and would require the use of more costly high-resolution monitors and associated video equipment. A higher resolution camera also would make more difficult and costly the transmission of video from the camera to the operations center for incident verification. Since a standard 525 line camera with a zoom lens is adequate for incident verification, the following resolution discussions center on the adequacy of 240 or 480 line resolution for automatic traffic parameter measurements. The use of 240-line resolution is considered since it can be obtained simply from the standard camera and reduces memory requirements. Lower resolution sensors are not discussed since they would not significantly lower the sensor costs, and they would not provide the resolution needed for incident verification.

The oblique view of the road by the WADS sensor makes it worthwhile to consider several different resolution measures. The first measure, D,

is just the reciprocal of the road resolution, or the distance along the road subtended by a single picture element. In Figure 6-2 the WADS sensor is shown mounted at height h, with the image sensor field-of-view (FOV) ϕ, and the maximum and minimum viewing distances along the road defined as d_{max} and d_{min}, respectively. Here D represents the distance along the road subtended by a single picture element which is viewing the road beginning at distance d. Let r be the resolution of the camera in picture elements per FOV. Then for a selected h, ϕ, r and d_{max} the corresponding d_{min} is given by

$$d_{min} = h \tan [\arctan (d_{max}/h) - \phi],$$

and D at a distance d along the road is

$$D = h \tan [\arctan (d/h) + \phi/r] - d$$

Several plots of D versus distance along the road are shown in Figure 6-3.

Road resolution is important in that it represents how well locations and changes of location (speed) of the vehicles can be measured. All of the curves in Figure 6-3 are for a camera with a resolution of 480 lines and d_{max} = 1320 feet (402 meters). For a resolution of 240 lines D would be approximately doubled. Curve 1 shows distance per picture element for a relatively wide FOV and a camera height of 25 feet (7.6 meters). This curve demonstrates that highly variable road resolution from this view geometry, with the location accuracy rapidly becoming useless for distances beyond 500 feet (152 meters). Curve 2 shows the substantial improvement resulting from a more uniform use of the camera resolution when mounted higher, at 100 feet (30.5 meters). This camera height gives good location accuracy out to around 1000 feet (305 meters). Of course, camera mountings of 100 feet (30.5 meters) have other obvious disadvantages. Curve 3 shows that, even with a 25-foot (7.6 meter) mount height, very good location accuracy can be obtained far from the sensor location by using a narrow FOV lens. However, a narrow FOV makes it necessary to lose coverage in the area near the sensor (at a 4:3 aspect ratio, even a $\phi = 36^{o}$ results in a horizontal coverage of only three 12-foot (3.66 meter) lanes at d_{min} = 33.1 feet (10.1 meters). Figure 6-3 shows that the road resolution for a 240 line image is perhaps

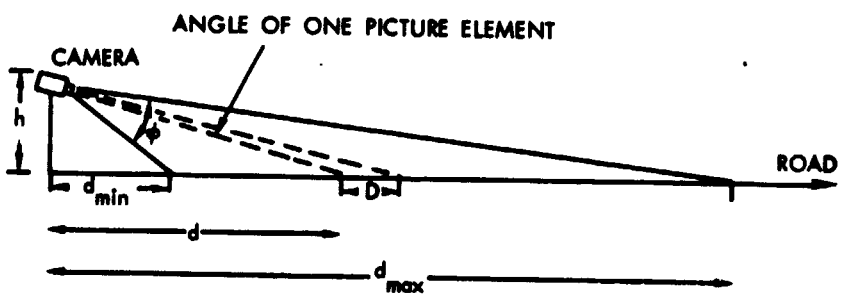

Figure 6-2. Depiction of Distance Along the Road per Picture Element

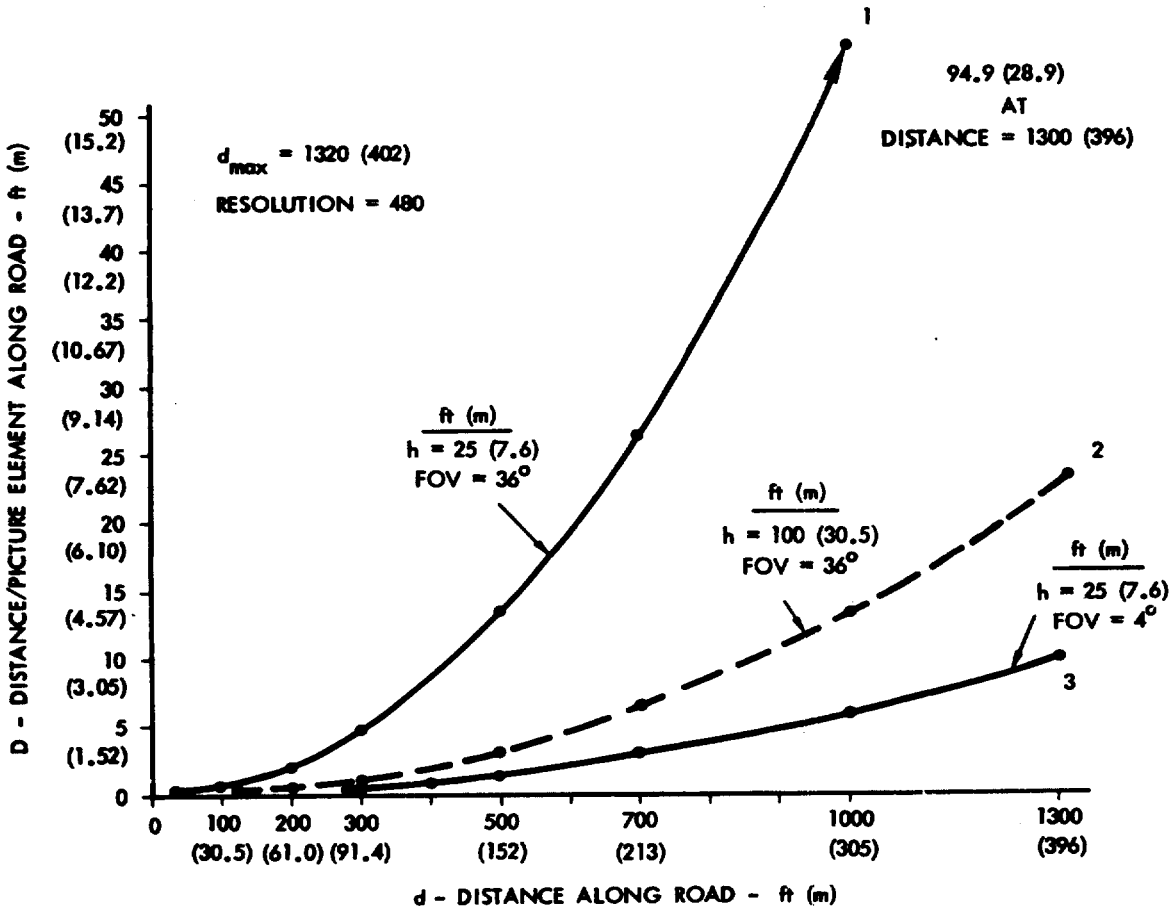

Figure 6-3. Distance per Picture Element Vs. Distance Along Road

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adequate out to 500 feet (152 meters). This is a satisfactory range for the time being, since it will be shown that other problems (e.g., occultation of vehicles) are more serious than resolution limitations. It is clear from Figure 6-3 that a combination of two sensors with a wide FOV lens and a narrow FOV lens would provide excellent road resolution over the entire range. This approach would be appropriate for later extending the range of WADS.

The above resolution measure was concerned with accuracy in locating a vehicle along the road. Another useful resolution measure is vehicle resolution R_V, which is defined as the number of picture elements subtended by a vehicle. Figure 6-4 depicts a vehicle at distance d along the road from the sensor mounted at height h. The sensor has a FOV of ϕ degrees and a resolution of r picture elements. The car is defined as having roof height H, and the length between nearest point of vehicle and furthest point of roof is L. Then the number of picture elements per vehicle (assuming no occultation) is

$$R_V = (r/\phi) \left\{ \arctan \left[(d + L) / (h - H) \right] - \arctan (d/H) \right\} .$$

Vehicle resolution is significant in that a small number of picture elements per vehicle (less than five) will make detection and parameter measurement for the vehicle very difficult. Figure 6-5 shows the plot of R_V for the same conditions used in the plots of distance per picture element in Figure 6-3. Curve 1 shows that, for a wide FOV, R_V becomes very low as the vehicle approaches a distance of 500 feet (152 meters). In contrast to the previous road resolution measure, the resolution of a vehicle is not significantly improved by a higher mount of the sensor. This can be seen from Curve 2 in Figure 6-5. A narrow FOV lens again can provide adequate resolution of the vehicle for distances all the way out to 1300 feet (396 meters), as shown by Curve 3. But, again, a narrow FOV cannot also cover the region near the sensor.

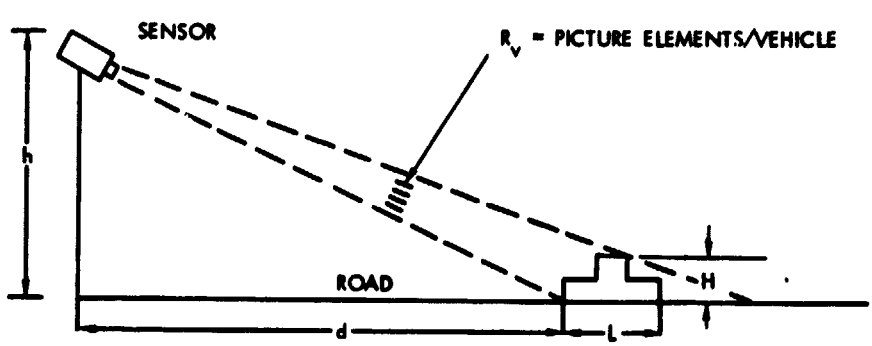

Figure 6-4. Depiction of Picture Elements per Vehicle

Thus a resolution of 240 picture elements should be adequate for detection and measurement of vehicles out to distances of 300 or 500 feet (91.4 or 152 meters). This distance could be increased by using both fields from the sensor, for a resolution of 480 elements; additional distance is feasible from a resolution standpoint if a combination of a narrow FOV lens and a wide FOV lens is used.

Occultation will likely be a more limiting factor than resolution in trying to use WADS at large distances. In conclusion, the resolution of the standard television camera appears to be adequate for WADS incident verification out to one-fourth of a mile (402 meters), and for parameter measurements out to 300 or 500 feet (91.4 or 152 meters).

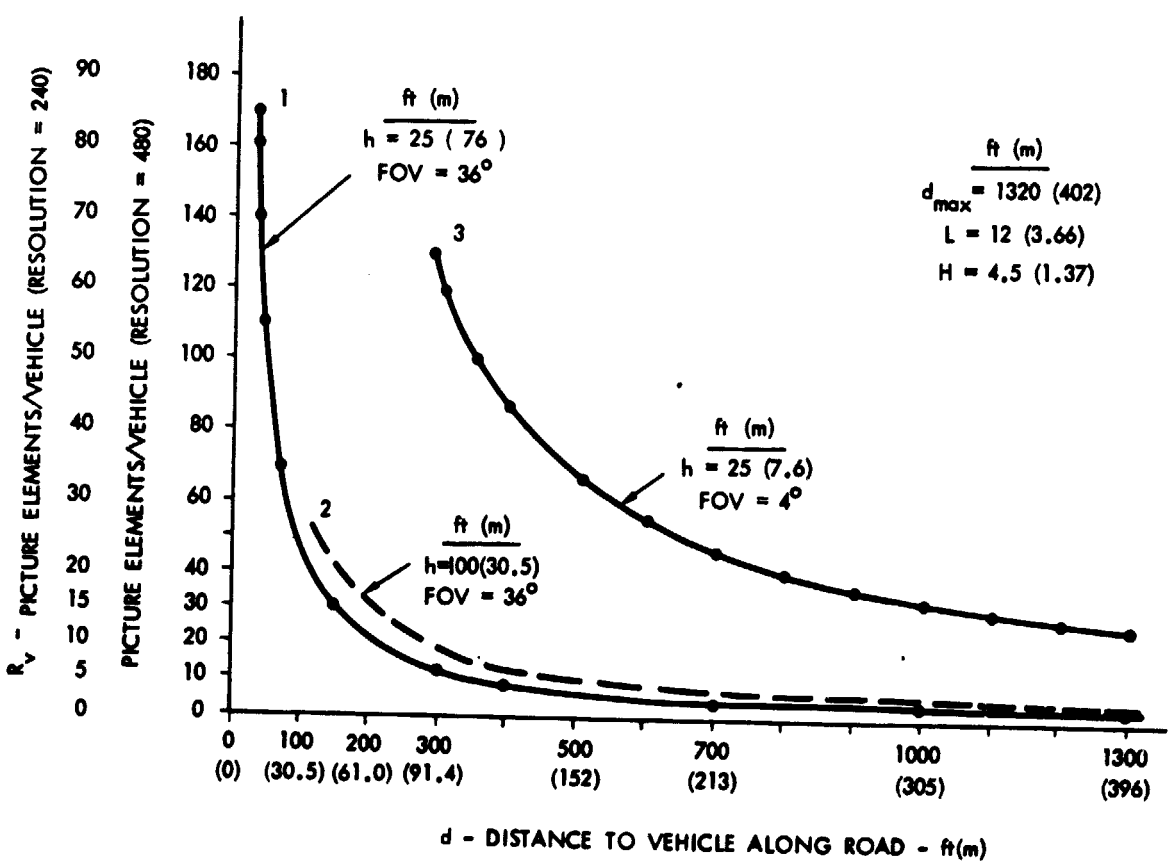

Figure 6-5. Vehicle Resolution Vs. Distance Along Road

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VEHICLE OCCULTATION IMPACT

Practical mounting limitations for the WADS sensor will limit its height to 25 to 50 feet (7.62 to 30.5 meters). This creates a view geometry that causes vehicles to occlude the view of other vehicles, and greatly complicates the automated measurement algorithm task. When the vehicles in the image are isolated, it is only necessary to distinguish between the moving vehicles and the stationary highway in order to detect, count, and estimate the length of vehicles. Vehicle count is desired for measuring traffic volume, and vehicle length is desired to measure occupancy. But when vehicles are merged in the image, it is necessary to distinguish the start and end points of the vehicles via the stream of merged moving vehicles. This latter task is much more difficult, expecially with the constraints on processing hardware cost and the real-time processing requirement of WADS. It should be observed that merging is less of a problem at night than in the day, since the headlights and taillights of vehicles merge, or become occluded much less often; however, vehicle length would be very difficult to estimate at night unless scene illumination is provided, or very expensive image sensors are used. The vehicle merging and occultation problem becomes more complex when the sensor view is not directly along the highway, and of course the amount of vehicle occlusion is very dependent on the distance of the vehicles from the sensor. Although the automated segmentation of merged vehicle images is still a possibility, its drastically greater level of difficulty suggests that the limits of WADS performance without it should be explored first.

Consider now the spacing required between vehicles in order to avoid occultation. In Figure 6-6 the WADS sensor is depicted

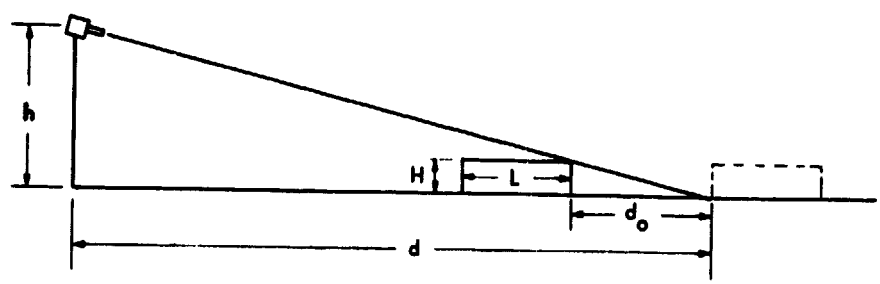

Figure 6-6. Minimum Gap Required to Avoid Occultation

at height h as viewing a vehicle of height H and length L. The front of the vehicle is at apparent distance d along the road and occludes a distance d_o in front of it. The occluded distance is given simply by

$$d_o = \frac{H}{h} d.$$

Assume a sequence of vehicles spaced with gaps of d_o; the occupancy measure for these vehicles is then

$$O_c = \frac{100.L}{L + d_o} .$$

Thus d_o represents the minimum spacing between the vehicles before occultation starts, while O_c represents the maximum occupancy before occultation. Table 6-1 lists values of d_o and O_c for various values of d and for h = 25 feet (7.62 meters), L = 17 feet (5.18 meters), and H = 4 feet (1.22 meters). Table 6-2 lists similar results, but with h = 100 feet (30.5 meters). These tables show that maximum occupancy without occultation decreases rapidly with increasing distance from the sensor. Although higher sensor installations enable substantially higher occupancy levels before occultation, it is clear that there is need to attempt detection, length measurement, and counting of vehicles as near to the sensor as possible.

The above results showed that occultation effects are reduced by making measurements close to the sensor. Now we will bound the minimum gap and maximum occupancy allowable without occultation affecting the measurements. This bound is derived by simply using the closest possible distance along the road of the field-of-view for counting and length measurements, while assuming the view of the road necessary between the vehicles for measurement purposes is negligibly small. Assume a WADS sensor is placed (Figure 6-7) at height h, with field-of-view ϕ, and is pointed at maximum distance d_{max} along the road. Assume the vehicles are of length L and height H, and define d_o' and O_c' as minimum gap and maximum occupancy required to avoid occultation when the vehicle measurements are assumed made at the closest distance possible to the sensor d_{min}.

For any given sensor configuration (h, ϕ, d_{max}), the bounds for gap and occupancy obtained from measurements made at d_{min} are given by

$$d_o' = H \tan \left[\arctan (d_{max}/h) - \phi\right],$$

and

$$O_c' = 100 \cdot L/(L + d_o'),$$

where

$$d_{min} = h \tan \left[\arctan (d_{max}/h) - \phi\right].$$

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Table 6-1. Minimum Gap and Maximum Occupancy for H = 4 Ft (1.22 M), L = 17 Ft (5.18 M), and h = 25 Ft (7.62 M)

d Ft (m)	d_o Ft (m)	O_c %
33.0 (10.1)	5.28 (1.61)	76.3
50.0 (15.2)	8.0 (2.44)	68.0
100 (30.5)	16.0 (4.88)	51.5
300 (91.4)	48.0 (14.6)	26.2
500 (152)	80.0 (24.4)	17.5
1000 (305)	160 (48.8)	9.60
1320 (402)	211 (64.3)	7.45

Table 6-2. Minimum Gap and Maximum Occupancy for H = 4 Ft (1.22 M), L = 17 Ft (5.18 M), and h = 100 Ft (30.5 M)

d Ft (m)	d_o Ft (m)	O_c %
50.0 (152)	2.0 (.610)	89.4
100 (30.5)	4.0 (1.22	81.0
300 (91.4)	12.0 (3.66)	58.6
500 (152)	20.0 (6.10	45.9
1000 (305)	40.0 (12.2)	29.8
1320 (402)	52.8 (16.1)	24.4

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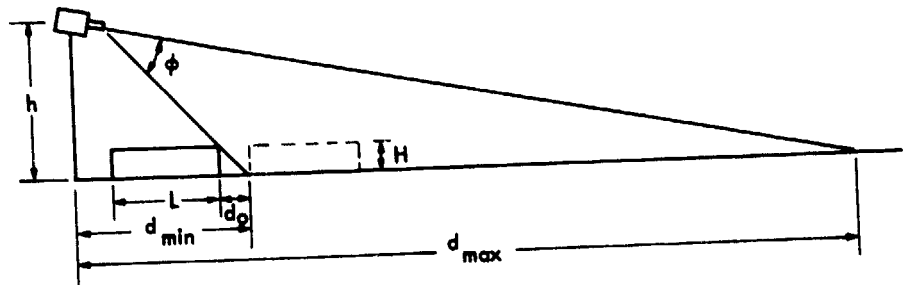

Figure 6-7. Minimum Gap to Avoid Occultation When the Measurement Is Made as Close to the Sensor as Possible

In Table 6-3 are listed resulting values of d_{min}, d_o', and O_c' for various sensor configurations (ϕ, h, d_{max}) and for car-sized vehicles, H = 4 feet (1.22 meters), L = 17 feet (5.18 meters). Table 6-4 lists results for the same conditions, for truck-sized vehicles, H = 12 feet (3.66 meters, and L = 60 feet (18.3 meters).

Table 6-3. Bounds for Minimum Gap and Maximum Occupancy for Vehicle of H = 4 Ft (1.22 M), and L = 17 Ft (5.18 M)

Sensor Configuration			Minimum Distance and Bounds		
ϕ	h	d_{max}	d_{min}	d_o'	O_c'
36	25 (7.62)	1320 (402)	33.1 (10.1)	5.29 (1.61)	76.3
36	25 (7.62)	500 (152)	31.0 (9.45)	4.96 (1.51)	77.4
36	50 (15.2)	1320 (402)	63.6 (19.4)	5.09 (1.55)	77.0
36	50 (15.2)	500 (152)	56.1 (17.1)	4.49 (1.37)	79.1
36	100 (30.5)	1320 (402)	118 (36.0)	4.71 (1.44)	78.3
36	100 (30.5)	500 (152)	92.2 (28.1)	3.70 (1.13)	82.2
52	25 (7.62)	1320 (402)	18.8 (5.7[illegible])	3.00 (0.914)	85.0
52	25 (7.62)	500 (152)	17.6 (5.36)	2.82 (0.860)	85.8
52	50 (15.2)	1320 (402)	36.1 (11.0)	2.89 (0.881)	85.5
52	50 (15.2)	500 (152)	31.6 (9.63)	2.53 (0.771)	87.1
52	100 (30.5)	1320 (402)	66.6 (20.3)	2.66 (0.811)	86.5
52	100 (30.5)	500 (152)	50.3 (15.3)	2.01 (0.613)	89.4

Table 6-4. Bounds for Minimum Gap and Maximum Occupancy for Vehicle of H = 12 Ft (3.66 M), and L = 60 Ft (18.3 M)

Sensor Configuration					Minimum Distance and Bounds		
ϕ	h		d_{max}		d_{min}	d_o'	O_c'
36	25	(7.62)	1320	(402)	33.1 (10.1)	15.9 (4.85)	79.1
36	25	(7.62)	500	(152)	31.0 (9.45)	14.9 (4.54)	80.1
36	50	(15.2)	1320	(402)	63.6 (19.4)	15.3 (4.66)	79.7
36	50	(15.2)	500	(152)	56.1 (17.1)	13.5 (4.11)	81.7
36	100	(30.5)	1320	(402)	118 (36.0)	14.1 (4.30)	80.9
36	100	(30.5)	500	(152)	92.2 (28.1)	11.1 (3.38)	84.4
52	25	(7.62)	1320	(402)	18.8 (5.73)	9.00 (2.74)	86.9
52	25	(7.62)	500	(152)	17.6 (5.36)	8.45 (2.58)	87.7
52	50	(15.2)	1320	(402)	36.1 (11.0)	8.66 (2.64)	87.4
52	50	(15.2)	500	(152)	31.6 (9.63)	7.58 (2.31)	88.8
52	100	(30.5)	1320	(402)	66.6 (20.3)	8.00 (2.44)	88.2
52	100	(30.5)	500	(152)	50.3 (15.3)	6.03 (1.84)	90.9

The following is a discussion of the observations which can be made concerning the impact on occultation by the choice of the sensor configuration (ϕ, h, d_{max}). Table 6-1 and Table 6-2 showed a significant advantage in reducing occultation at a given distance along the road by having a higher sensor mounting. However, Tables 6-3 and 6-4 show that the minimum obtainable occultation for a sensor configuration (that obtainable at distance d_{min}) is not significantly affected by sensor height. The reason for this is that d_{min} is larger for a sensor which is mounted higher, as also shown in Table 6-3 and Table 6-4. These tables show that d_{min}, d_o', and O_c' are also not significantly affected by d_{max}. Maximum occupancy before occultation is not lower for trucks in Table 6-4, but this is because the occupancy in Table 6-4 is based on the assumption of a uniform spacing of vehicles which are all very long as well as high (trucks). Clearly, occupancy measurement and occultation problems will be more difficult for short vehicles which are high, or for trucks mixed with smaller vehicles. A larger field of view does considerably reduce occultation at d_{min}, but the improvement in maximum occupancy may not be significant mostly because the O_c for ϕ = 36 degrees is already very high. The selection of ϕ thus becomes a trade-off between resolution and occultation, but for low sensor heights, ϕ will need to be at least 36 degrees in order to have a wide enough horizontal field of view.

From the above one can conclude that vehicles can be detected, counted, and measured for length without major occultation problems for even high occupancy traffic approaching 80%, provided the measurements are made at d_{min}. Occultation at d_{min} is affected little by changes in d_{max} and h; however, for distances beyond d_{min} occultation rapidly increases and increasing the sensor height substantially reduces occultation. But even for a sensor at a height of 100 feet (30.5 meter), occultation will create merging of the vehicles and make difficult the counting and length measurements for distances along the road of more than several hundred feet. These measurements would be further complicated by the lower resolution at these greater distances. Therefore, it is desirable to have a WADS algorithm approach for which the initial detection, counting, and length measurement of the vehicles is performed in the near field of the sensor (vicinity of d_{min}).

VEHICLE LENGTH AND HEIGHT ESTIMATION

Height and length of vehicles are not of primary interest as traffic flow parameters, but as is described below they are necessary to obtain direct measures of occupancy, velocity, and vehicle location via an image sensor. Current loop sensing techniques achieve an indirect occupancy measure by measuring presence and using an average length for vehicles. A direct measure of occupancy must actually measure the length of vehicles. The length measurements made from a WADS image sensor will be affected by the height of the vehicle. Likewise the measurements of vehicle location and changes of vehicle location per time (velocity) are affected by vehicle height. Refer to Figure 6-8. The WADS sensor is at height h viewing a vehicle covering the image of the highway from distance d_1, to distance d_3. Observe that the vehicle could have many different dimensions (e.g., H_1 by L_1, or H_2 by L_2). Let d_1 denote the distance along the

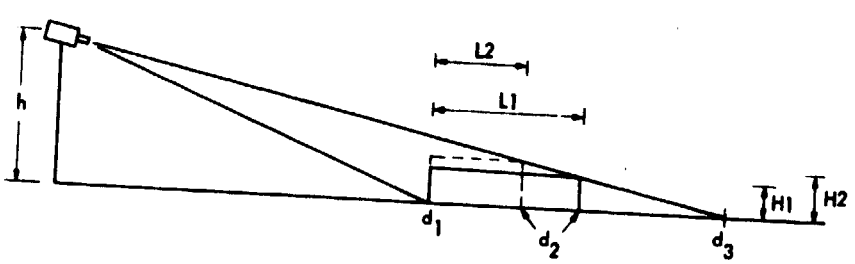

Figure 6-8. Diagram Showing How Two Vehicles of Different Length and Height Extend Over Same Region of Image

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road to the closest part of the vehicle, d_2 the distance to the furthest part of the vehicle, and d_3 the furthest distance occluded by the vehicle (apparent location of front of vehicle in image). Only d_1 and d_3 are directly observable from the image data. If d_1 were always available from the image, then measures of vehicle location and velocity could be directly obtained without consideration of vehicle height. Unfortunately, as discussed previously, the view geometry of WADS will often cause occultation of the nearest part of the vehicle, making direct measurement of d_1 impossible. Therefore, a more distant part of the vehicle is used, and vehicle location and velocity must be estimated from d_3 and an estimate for the height of the vehicle. Let L and H be the actual length and height of the vehicle, respectively. Then the location of the furthest part of the vehicle d_2 in terms of the observed d_3 is, by similar triangles,

$$d_2 = \left(\frac{h-H}{h}\right) d_3 \ .$$

Likewise, the actual velocity of the vehicle V_2 in terms of the observed velocity V_3 is

$$V_2 = \left(\frac{h-H}{h}\right) V_3 \ .$$

Note that d_2 and V_2 are obtained without observations of d_1. However, measurements of vehicle length require observation of d_1, which suggests that length measurements will need to be made in the near field of the WADS sensor to avoid occultation of the vehicle at d_1. From Figure 6-8 it can be seen that the actual length of the vehicle in terms of the vehicle height and the observations d_1 and d_3 is

$$L = (d_3 - d_1) - \frac{H}{h} d_3 \ .$$

Above we have demonstrated the dependency on H of the measurements for vehicle occupancy, location, and velocity. An actual estimate for H will be defined in Section IX of this report. At this time only the sensitivity to errors in the estimate of H is presented. Let $P.E._{d,v}$ be the percent error in the estimate for distance (location), or velocity caused by the error in the estimate for H; and let $P.E._H$ be the percent error in the estimate for vehicle height. Define $R_{d,v}$ as the ratio of percent error in distance and velocity to the percent error in estimating H. Then $R_{d,v}$ is given by

$$R_{d,v} = \frac{P.E._{d,v}}{P.E._H} = \frac{H}{h-H}$$

A plot of $R_{d,v}$ vs. h is given in Figure 6-9, which shows that location and velocity estimates will be very insensitive to errors in estimating H when H is around 4 feet (1.22 meters), for example with cars. However, high vehicles such as trucks will require estimates of H almost as accurate as the desired accuracy for estimating location, or velocity, unless the sensor height approaches 100 feet (30.5 meters).

Define $P.E._L$ as the percent error in the estimate of L due to the error in estimating H, and define R_L as the ratio of $P.E._L$ to the $P.E._H$.

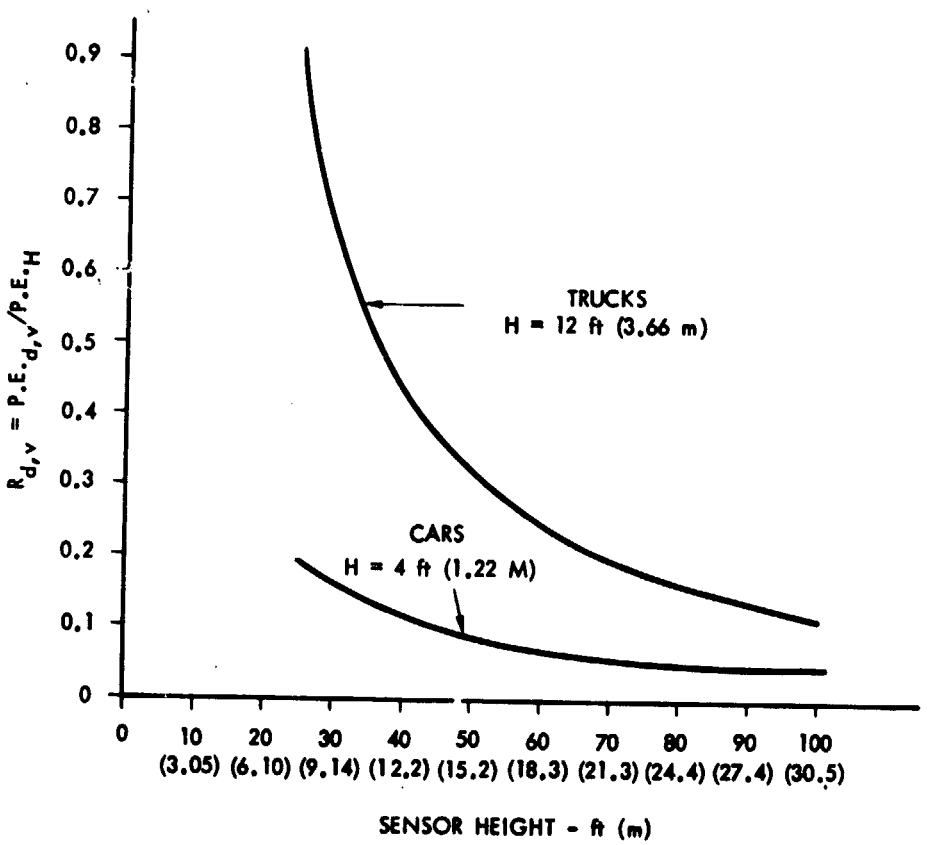

Figure 6-9. Ratio of Percent Error in Location or Velocity to Percent Error in Vehicle Height Vs. Sensor Height

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Then R_L corresponding to an estimate for a vehicle whose furthest distance is d_2 is given by

$$R_L = \frac{P.E._L}{P.E._H} = \frac{H}{(h-H)} \frac{d_2}{L} .$$

A plot of R_L for various situations is given in Figure 6-10. Observe that the estimate for L rapidly loses accuracy as d_2 increases; furthermore, occultation would often make estimation of L extremely difficult for distances much beyond 100 feet (30.5 meters) from the sensor.

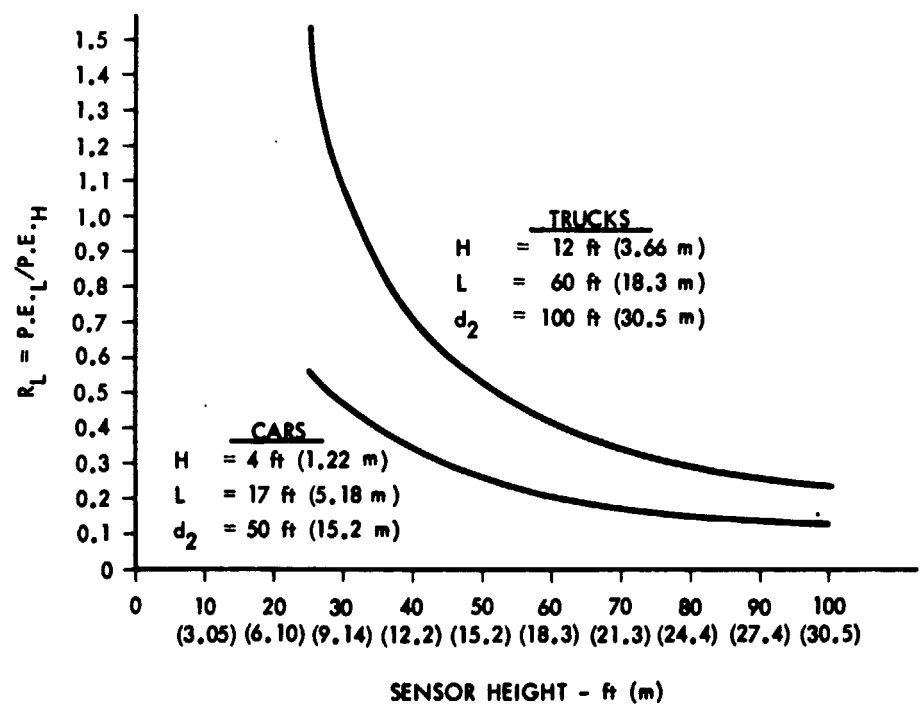

Figure 6-10. Ratio of Percent Error in Length to Percent Error in Vehicle Height Vs. Sensor Height

In summary, the above results show that vehicle height impacts the estimates for location, velocity, and occupancy. Height uncertainty causes few problems for cars, but an estimate of vehicle height is important for high vehicles such as trucks. All estimates affected by vehicle height uncertainty are much improved in accuracy by increases in sensor height. Vehicle length estimates in particular need to be made in the near field of the sensor to avoid severe problems with occultation, resolution, and sensitivity to vehicle height uncertainty. Since vehicle length and height do not change as a vehicle moves through the field of view, there should be strong preference toward an algorithm approach which estimates these parameters in the near field and is able to use these estimates in assisting other far field estimates. Finally, note that length and height cannot be estimated solely from headlights, or taillights at night. Satisfactory performance for cars is still likely by using an average estimate for H (especially since averaged measures of traffic flow are adequate). But near field illumination at night might be required to reduce the errors for trucks.

SELECTION OF ALGORITHM APPROACH

The selection of an algorithm approach depends much on the specific requirements for the sensor, but since this sensor is very different and new it is currently difficult to define a meaningful set of requirements. The algorithm must provide the usual traffic measures of average volume, occupancy, and velocity, but even for these parameters there are a large range of possible space interval, or time interval averages that may be desired. Furthermore, other new traffic parameters are possible with an image sensor, such as measures of lane changing, velocity variance, acceleration, shoulder parking, and even individual vehicle behavior. An image sensor presents so many new possibilities that one cannot now adequately predict what new parameters are important in monitoring traffic flow. An algorithm developed to provide a specific set of measurements would likely soon be viewed as making the wrong measurements. It is also not feasible to attempt developing algorithms to measure all the possibly useful traffic parameters.

A useful algorithm approach in this situation is to use two stages in the image processing. The first stage is a general preprocessing stage to replace the huge volume of image data with a greatly reduced representation, but from which nearly any traffic parameter set can still be acquired. The reduced representation should be such that the second stage of processing to acquire the specific parameter set is simple to define and can be changed easily.

Vehicle traffic can be viewed as having two types of information: (1) the vehicle description, and (2) the vehicle location as a function of time. Examples of vehicle descriptions are length, height, width, type, etc., and this type of information does not generally change

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with small changes in location and time. Therefore, this information need only be acquired once per each vehicle. Vehicle location as a function of time is simply the vehicle trajectory, which inherently defines the total dynamic properties of the vehicle (location, velocity, acceleration, lane changing, etc.). Now we define a Vehicle Detection and Tracking Algorithm (VDTA) as a general preprocessing algorithm for images of traffic which (1) detects vehicles and acquires vehicle descriptions, and (2) tracks each detected vehicle through the field of view of the sensor in order to define vehicle trajectories. The VDTA is a general preprocessing algorithm in that the combination of vehicle descriptions and trajectories provides a reduced representation of the data which is still adequate for obtaining almost any set of traffic parameters. For example, the preprocessed data of the VDTA can conceptually provide, through very simple specific processing, selected measures of occupancy, volume, velocity, acceleration, lane changing, stopped vehicles, etc. Furthermore, the user-specific processing can choose and change easily at any time the interval of space and time averaging desired for the parameters selected. Thus the VDTA is an extremely flexible general preprocessing approach for image data of traffic.

Consider now an example of the extent to which the VDTA concept is a reduced representation of the image data. The original image data generates 73.7 million bits per second with a resolution of 480 by 640 elements per field. Assume the image covers 500 feet (152 meters) of five lanes with 20-foot (6.1-meter) vehicles spaced every 50 feet (15.2 meters) along each lane and traveling at a speed of 50 ft/sec (15.2 m/sec). In each lane there is a new vehicle entering the field of view once per second. Assume there are 10 different vehicle descriptions (length, height, etc) at 8 bits each for every vehicle. Then the vehicle description part of the VDTA representation requires 80 bits/second/lane. Assume the trajectory of each vehicle in the field of view is described with 8 bits in the x direction and 8 bits in the y direction for every 25 feet (7.62 meters) of motion along the road. Then each vehicle requires 32 bits/second to define the trajectory. There are 10 vehicles per lane giving a data rate of 320 bits/second/lane. Combining the vehicle trajectory and description data, the rate is 400 bits/second/lane, or for all five lanes the total data rate for the VDTA representation is 2000 bits per second. This data rate could easily be reduced by about another order of magnitude, but already it is low enough for phone line transmission and provides a tremendous data reduction from the 73.7 million bits per second of the original image data. Yet the VDTA representation gives much flexibility and convenience for extracting out the final specific traffic flow parameters, or even direct incident indications. Therefore, the VDTA approach is recommended as a general preprocessing of the image data for the WADS.

DISCUSSION OF VEHICLE DETECTION AND TRACKING CONCEPT

The VDTA as a concept is very general and could be applied to any type of vehicle, traveling in any direction. For example, the concept is also applicable to vehicles on off-ramps, on-ramps, or urban networks. The limitations of the VDTA will originate from the inherent limitations of the WADS image sensor view geometry. The previous discussions in this section demonstrated the impact of the view geometry in terms of vehicle occultation and resolution considerations. These discussions suggested that vehicle detection and description was feasible in the near field of the sensor (within 100 to 200 feet (30.5 to 61 meters) of the sensor), and became very difficult rapidly with increases in distance from the sensor. Therefore, the logical starting point for the VDTA is to develop vehicle detection and description capability for the near field.

It is of course desirable to have the WADS provide traffic flow monitoring over as large a distance as possible. Vehicle descriptions necessary for volume and occupancy measures would be very difficult and perhaps impossible to obtain directly for distances beyond 200 ft (61 M). However, measurements necessary for tracking vehicles can be made for distances far beyond 200 feet (61 meters). Tracking of vehicles, or groups of vehicles is much less sensitive to resolution or occultation effects, and it is anticipated that the vehicles could be tracked out to distances between 500 and 1000 feet (152 to 305 meters). Since the description of vehicles does not change as the vehicles travel from near field to far field, the ability to track vehicles in the far field is all that is needed to substantially extend the distance over which the full measurement capabilities of the WADS apply. There are of course serious problems in applying this concept to on-coming traffic, because there is an indefinite time delay between the tracking of the vehicles in the far field and the descriptive information obtained about the same vehicles when they reach the near field. Consider the situation when an incident is preventing the vehicles from reaching the near field. Therefore, the image processing approach which appears to make the best use of an image sensor, within the WADS constraints, is the VDTA concept applied to receding traffic. Of course, the VDTA concepts are still applicable to traffic in any direction in the near field.

SUMMARY OF ALGORITHM TECHNOLOGY FOR WADS

There are many algorithm techniques discussed in the literature which are applicable to WADS in a general sense, but none of these techniques are directly applicable to WADS. The sample rate and resolution of standard television cameras are adequate for WADS, and the algorithm performance will be mostly limited by view geometry (occultation). While the signal of an infrared television sensor is slightly preferable, the large increase in costs over the standard visual television camera is not justifiable. From a computation standpoint, the processing algorithm must initially use feature

extraction techniques. The best features appear to be a combination of cross-lane and along-lane sequences of samples from the image. The recommended algorithm approach is a Vehicle Detection and Tracking Algorithm which detects and describes the vehicles in the near field, and tracks the vehicles in the far field. The vehicle description must include vehicle length and height. The VDTA concept is applicable to all traffic in the near field, but only applicable to receding traffic in the far field. The VDTA is a general preprocessing algorithm which reduces the very high rate image data down to phone line data rates. A reduced representation of the image by the VDTA then enables any user to very simply obtain any of a very wide range of desired specific traffic parameters.

Automatic monitoring of traffic appears to be feasible and to offer large potential advantages over current monitoring approaches. However, the algorithm needed for WADS does require advances over the current state of algorithm technology, due to the constraints of real-time processing and low cost. While good performance appears feasible, the far field distance and severe weather limitations can only be accurately assessed by experiments with a breadboard model.

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REFERENCES

6-1. L. Kanal, "Patterns in Pattern Recognition: 1968-1974," IEEE Trans. Inform. Tehory, Vol. IT-20, pp. 697-722, Nov. 1974.

6-2. K. Fu and A. Rosenfeld, "Pattern Recognition and Image Processing," IEEE Trans. Computers, Vol. C-25, pp. 1336-1346, Dec. 1976.

6-3. J. G. Raudseps, " Automatic Extraction of Highway Traffic Data From Aerial Photographs," U. S. Department of Transportation, Report No. DOT-TSC-FHWA-75-1, April 1975.

6-4. J. R. Whitten and F. A. Ludewig, "A Study to Determine the Feasibility of Development of An Area Traffic Surveillance and Control System," Federal Highway Administration, Washington, D.C., Prepared by General Electric, Schnectady, N. Y., PB183848, Feb. 1969

6-5. Research Staff, "Investigation of Traffic Dynamics by Aerial Photogrammetry Techniques," Transportation Research Center, Dept. of Civil Engr., Final Report EES278, Ohio State Univ., Columbus, Ohio, Feb. 1975.

6-6. J. A. Feldman and Y. Yakimovsky, "Decision Theory and Artificial Intelligence: I.A. Semantics - Based Region Analyzer," Artificial Intelligence 5 (1974), 349-371.

6-7. Y. Yakimovsky, "Boundary and Object Detection in Real World Images," Technical Memorandum 33-709, Jet Propulsion Laboratory, Nov. 1974.

6-8. C. Cafforio and F. Rocca, "Methods for Measuring Small Displacements of Television Images," IEEE Trans. Inform. Theory, Vol. IT-22, pp. 573-579, Sept. 1976.

SECTION VII

TEST DATA ACQUISITION

In order to investigate image sensor technology and image processing techniques for traffic monitoring, it was necessary to acquire and study a large number of traffic scenes. There are many variations in cameras, camera viewing angle and height, time of day, weather, and traffic direction and conditions. We collected data with a portable videotape recorder and camera, and converted some of it to computer compatible tape. Most of the test data originated from traffic scenes in the Los Angeles, California area. Some of the traffic scenes were recorded in conjunction with the California Department of Transportation, which was very helpful in sharing with us information they were collecting on various television cameras. They also provided us with standard inductive loop sensor outputs corresponding to some recorded scenes.

The test data is currently in an unedited form and is far from being comprehensive, but it will be useful for continuing investigations of the automated traffic monitoring algorithms. If this test data can be useful to other research activities, arrangements can be made to obtain copies by contacting the authors.

Below is a listing of the various types of traffic scenes in the test data.

1. <u>Time of day</u>

   Day
   Sunset
   Night

2. <u>Weather</u>

   Clear
   Rain
   Snow
   Fog

3. <u>Traffic Condition</u>

   Approaching at various angles
   Receding at various angles
   Heavy
   Light

4. <u>Camera height</u>

   25 feet (7.62 meters)
   30 feet (9.14 meters)
   35 feet (10.7 meters)
   100 feet (30.5 meters)

5. <u>Camera types</u>

Vidicon	ISIT
SIT	CCD

SECTION VIII

BREADBOARD HARDWARE CONCEPTUAL DESIGN

INTRODUCTION

The conceptual design of the data processor and electronics may be divided into a number of categories to emphasize and clarify functional relationships between the sensor, the data analysis algorithms, the local control, and the communications interface. These are

(1) Sensor interface and buffering.

(2) CPU and memory.

(3) Communications interface.

(4) Local control interface.

(5) Local testing and servicing.

(6) Power and failure modes.

The design features of the breadboard model (already recommended) as they relate to the conceptual design will also be discussed. It is assumed that the sensor generates image data at standard television rates. Some of the items listed above are treated in a somewhat cursory manner. This is justified by the fact that there are still many unknowns as to exact requirements and feasibility in terms of cost. Many "features" are possible, but how do they really affect overall performance and how can we predict what the operator/machine interface problems are going to be? Hopefully, a breadboard model will help bring these questions into focus in addition to testing basic algorithm and data processing feasibility.

The time spent in building and using a breadboard WADS will also help the field design of the data processing electronics to take advantage of higher performance microprocessors and memories. As noted in the state-of-the-art study section, the best technology for this application is just beginning to emerge in the commercial marketplace. Because of rapid new developments in this area of technology, the cost and development problems associated with the data processing hardware may be minimal compared to such items as installation of a remote site, communications, or overall maintenance.

SENSOR INTERFACE AND BUFFERING

For reasonable resolution of images using digital processing, the data rates at the sensor/processor interface are too high for direct storage into the main memory used by the processor. Therefore, a buffer memory of some sort is required. Two approaches were examined in some detail and a third way was considered briefly. One approach is shown in Figure 8-1. It uses a first-in-first-out (FIFO) buffer which acts as a

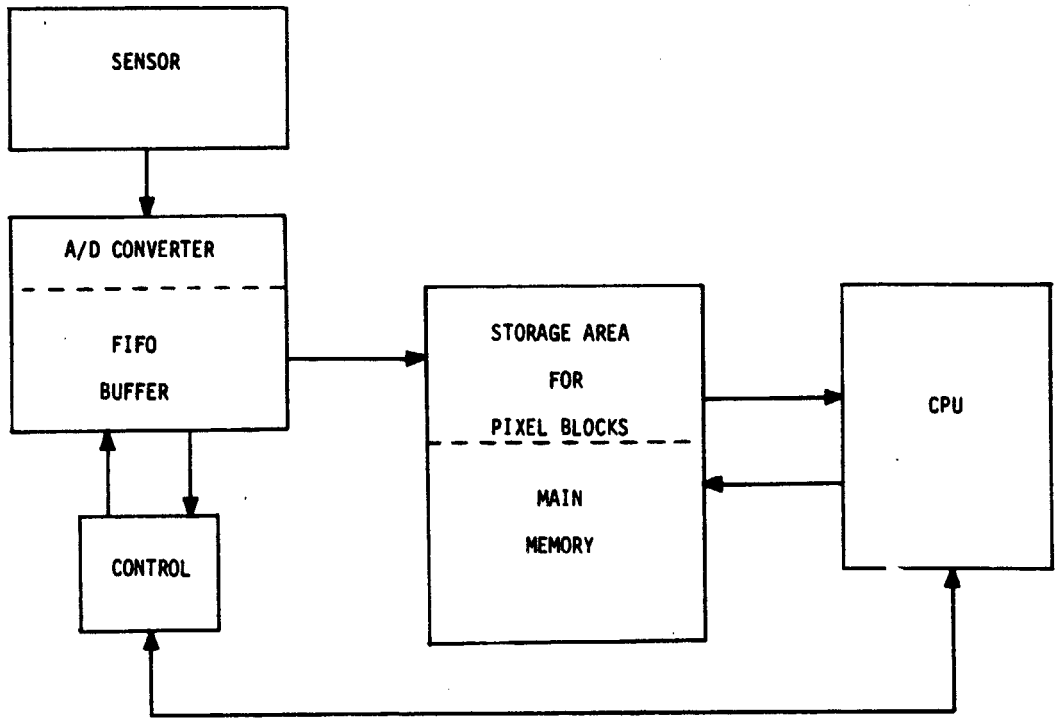

Figure 8-1. Basic Design with FIFO Line Buffer

queuing device to store a fixed number of lines of data from each image. The position of the lines in the image would be under program control. For example, a design using two groups of 16 consecutive lines each would allow blocks of picture elements (pixels) from two vertically separated areas of the image to be extracted from a given field for analysis. A design of this type was done in sufficient detail to determine the feasibility and the cost of the major components. About 600 integrated circuits would be required to buffer two sets of 16 lines each. The FIFO circuits would account for 256 of this number and would be the most expensive. The only currently available FIFO circuit fast enough for the 4 to 5 MHz pixel rate is the Monolithic Memories part MMI-67401. It is currently selling for $28.00 in quantities of 100 - obviously too expensive even for the breadboard. Even if the price decreased by a factor of five, the need for 256 devices still makes it fairly expensive for a final design.

The second approach is to use a random access memory (RAM) type of buffer. The basic design for this configuration is illustrated in Figure 8-2. As shown, the buffer is alternately connected to the sensor and the main memory. A full field of image data is digitized and stored. Then, during the next field time the input/output port of the buffer is electronically switched to a direct memory access channel into the main memory, and image data from any portion of the picture may be moved into main memory. A more efficient variation would be the use of a dual port memory to eliminate the need for switching and maximize the time for data sampling. At this time, 'off-the-shelf' memories with sufficient speed to accept the data rate of the sensor are not available in a dual

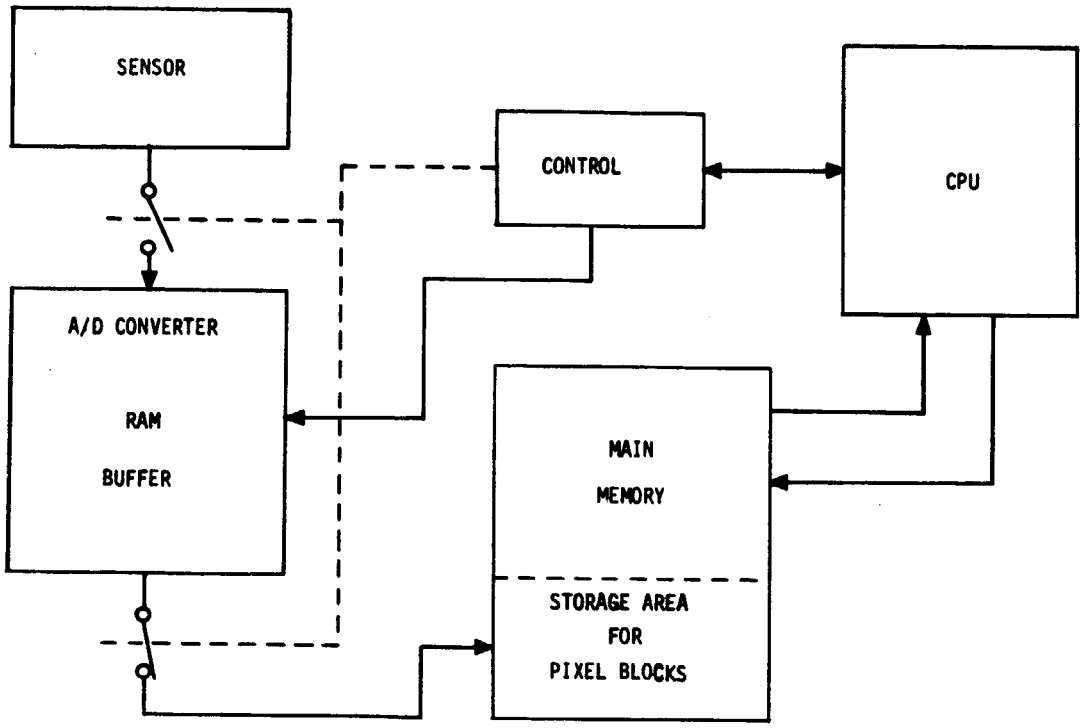

Figure 8-2. Basic Design with Full Field Buffer

port configuration. Therefore, the switching described above would be required for the breadboard model unless a special memory design were done, and this would not be cost-effective.

For a final design of the processing system, a further extension of the use of a RAM buffer is possible. The main memory for the CPU could be designed as a dual port memory and the digitized data from the sensor could be loaded directly into a predetermined storage area. This would obviate the need for both switching and buffer-to-main-memory transfers because the buffer would already be part of main memory. The Varian V77-400 minicomputer mentioned in the state-of-the-art section of this report is an example of this type of architecture, but its dual port memory (available as an option) is not fast enough to accommodate the high data rate from the sensor. This dual port approach will be discussed further in the next section.

Between the sensor and the buffer memory is a high speed analog-to-digital converter. This device samples the analog video signal from the sensor and converts the voltage level at that moment into a digital representation. The number of bits for each conversion determines the number of shades of gray that the full scale voltage can be divided into. Currently available A/D converters that can handle standard television scan rates cost about $1000 in single quantity. In the 1979-1980 time frame, this cost will probably be below $100 in quantities of 100.

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CENTRAL PROCESSING UNIT AND MEMORY

Reference to either of the basic design figures just discussed illustrates the functional position of the central processing unit (CPU). The tasks to be performed by the CPU in the WADS data processing system are the same as those in most computer systems. However, most of the processing time is dedicated to the image data. The speed of processing required (including any buffer-to-memory transfers) is high, but tasks other than taking care of image data proceed at a much lower rate. These low rate tasks include such things as "housekeeping" and sending and receiving messages over the communication link.

Because of this dedication and high performance, a custom design for the final field unit is indicated. Most of the customizing may be done in the memory to achieve the dual part architecture discussed above. A CPU architecture that appears suitable to the WADS application and could be compatible with a dual port memory was discussed in the state-of-the-art study. This is the TMS 9900 that uses blocked workspaces in memory and is generally referred to as having a memory-to-memory architecture. Continuing work on the vehicle detection and tracking algorithms indicates that the types of computation and data manipulation needed could be done faster with a memory-to-memory architecture than with a memory-to-register type.

A bit-slice device currently available that could be used in the development of a custom design with memory-to-memory architecture is the SN545481 from Texas Instruments. If the character of the algorithms or the sensor data rate should change so that memory-to-register processing would be more efficient, then a bit-slice family such as the AM 2900 from Advanced Micro Devices should be considered. In either case, it is recommended that no custom design be started until field-tested algorithms have been developed. A breadboard model using a minicomputer is a good vehicle for doing the field testing, and such a system would answer many questions that no amount of analysis can resolve. An additional advantage in delaying design of the processing system is that full use can be made of the constant industry trend toward increased performance and maintainability at lower cost.

Memory architecture has already been discussed above. It is anticipated that the device technology for both buffer and main memory will be the same. The cost of memory devices will be a significant part of the total data processing system costs. At this point in time the most likely candidate for low cost and high density in the 1979-1980 time frame is the 16K-64K bit RAM. For example, Mostek, Inc. has just introduced a 16K bit device with a 150-nanosecond access time - fast enough to use in the design of a buffer memory for WADS. An array of 32 such devices could buffer 64,000 pixels. This is the same overall size as the buffer planned for the breadboard, but it will likely be implemented with 4K RAM devices to take advantage of existing "off-the-shelf" memory designs.

The important factors to remember in the design of the data processor are the high data rate from the sensor and the need to extract selected portions of that data while minimizing the time taken for buffering and transferring.

COMMUNICATIONS INTERFACE

This is the operational interface between the WADS sensor/data processing system and the outside world. Information will flow in both directions across this interface. The information from the remote site will be either low rate data consisting of the various traffic parameters calculated by the algorithms or higher rate data for incident verification. The calculation and transmission of basic traffic parameters are considered to have the highest priority for the conceptual design.

Input/output ports on the data processing system may be accommodated through the standard I/O facilities of the processor or a more direct connection could be made to the buffer memory. A "frozen" field of image data would be available from the full field RAM buffer (another factor in favor of this type of sensor-to-processor buffering). The best way to send this data back to the central site has not yet been determined and could be included as part of the breadboard design work.

LOCAL CONTROL INTERFACE

For the breadboard design, this interface will not need to exist even if the sensor must be located remotely from the operator. Pan, tilt, zoom and focus will all be controlled by manually adjusting the lens and mount or, if the sensor is located on a pole, control can be effected by watching a video monitor and using a cable to send signals up to the mounting and lens hardware. The data processing system does not need to be involved in such operations.

For a final field design, the need for this interface will depend on whether or not an image of the scene can be returned to the operator at the central site in a manner that will allow good feedback for position and focus adjustments. If changes as a result of control commands are not apparent to the operator in a reasonably short period of time, the process will be very frustrating.

From a data processing hardware point of view, status and control signals exchanged with the sensor hardware will be very low rate and easily handled by standard I/O interfaces. They should also be low in cost.

LOCAL TESTING AND SERVICING

This is another area of the WADS design that is not important for the breadboard model. A local video monitor will give a continuous check of sensor operation and the data processing system can be checked by observing the output on a video display terminal and/or running suitable diagnostic routines.

For a field design, local testing and servicing is an important consideration from a maintenance cost point of view. Figure 8-3 shows the functional position of the basic test "points." By testing on either

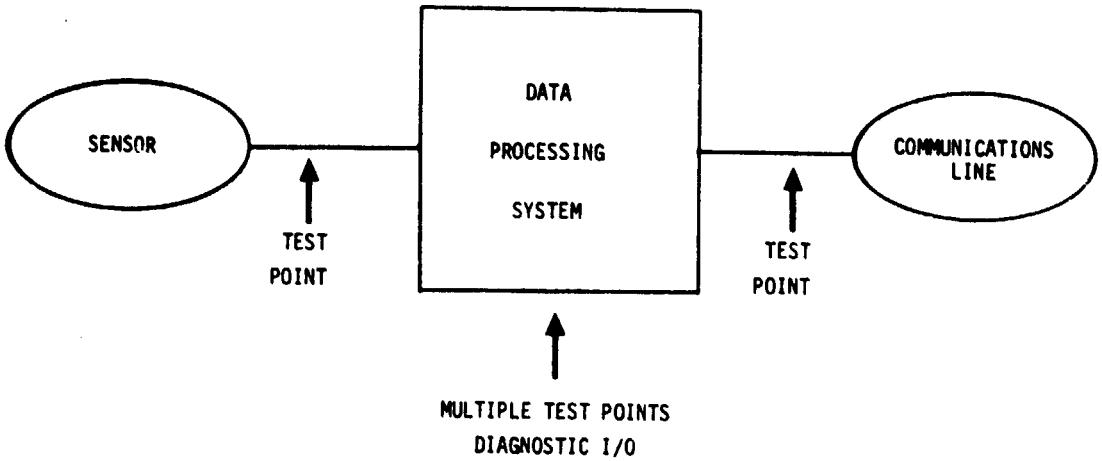

Figure 8-3. WADS Remote Site Testing and Servicing

side of the data processing system, the failure of the sensor or the communications lines can be isolated. By injecting test signals and/or using diagnostic programs, failures within the data processing system may be localized to subsystems such as the memory, CPU, A/D converter or control and communications interfaces. Proper modular design of the WADS should allow a service technician to replace a defective subsystem module and restore normal operation. A test set capable of isolating problems to the module level could easily be fitted into a small suitcase type of container and, as a rough estimate, have a hardware cost of $3000 to $5000 in small quantities. This test set concept is very common wherever field support of sophisticated electronics is required.

POWER AND FAILURE MODES

Basic power for the field design will be derived from the power for lighting that services the installation area and should be fairly reliable. However, even momentary power fluctuations or outages may cause either programs or data or both to be lost or scrambled. When this occurs, there must be some recovery mode that allows the system to revert to some known state and resume operations. For the breadboard system, this reinitializing will be done by the operator using a floppy disc tape cassette to reload the programs through the display terminal. For the field design, the programs will have to be stored in ROM from which they would be accessed automatically after power was restored. Commands could also be sent over the communications link to effect initializations from certain types of partial failures. Nonrecoverable failures such as sensor or electromechanical failures would require field service.

BREADBOARD SYSTEM HARDWARE

A brief description of the proposed breadboard system hardware is now in order to summarize and expand on what has been mentioned in the

preceding sections. The major components of the proposed breadboard system are shown in Figure 8-4. Figure 8-5 illustrates a more logic design-oriented view of the interface between the sensor, buffer and CPU. The RAM buffer is an off-the-shelf video display memory. The CPU is a minicomputer with 32K words of high performance memory (cycle time, 350 nanoseconds). A display terminal acts as the operator console and provides visual monitoring of system performance. The floppy disk is required for program development and for data storage during performance analysis. The printer will augment the display terminal by providing hard copy outputs.

On the "front end," the sensor will be a Sanyo VC 500 video camera with built in view finder. This is the camera that has been used in gathering field data for the algorithm development work. Video output from the camera will be digized by a Computer Labs Model MATV-0808 A/D Converter. This is a small, modular device, 6 x 5 x 0.75 inches (15.2 x 12.7 x 1.9 cm); it includes sample-and-hold circuits with an aperture time of only 30 picoseconds.

Referring again to Figure 8-5, those parts of the breadboard that will have to be designed are the byte/word gating (assembles two 8-bit bytes into one 16-bit word), sync stripper, control logic, and the sequential address generator. Also, some additional logic may be needed to interface with the DMA controller.

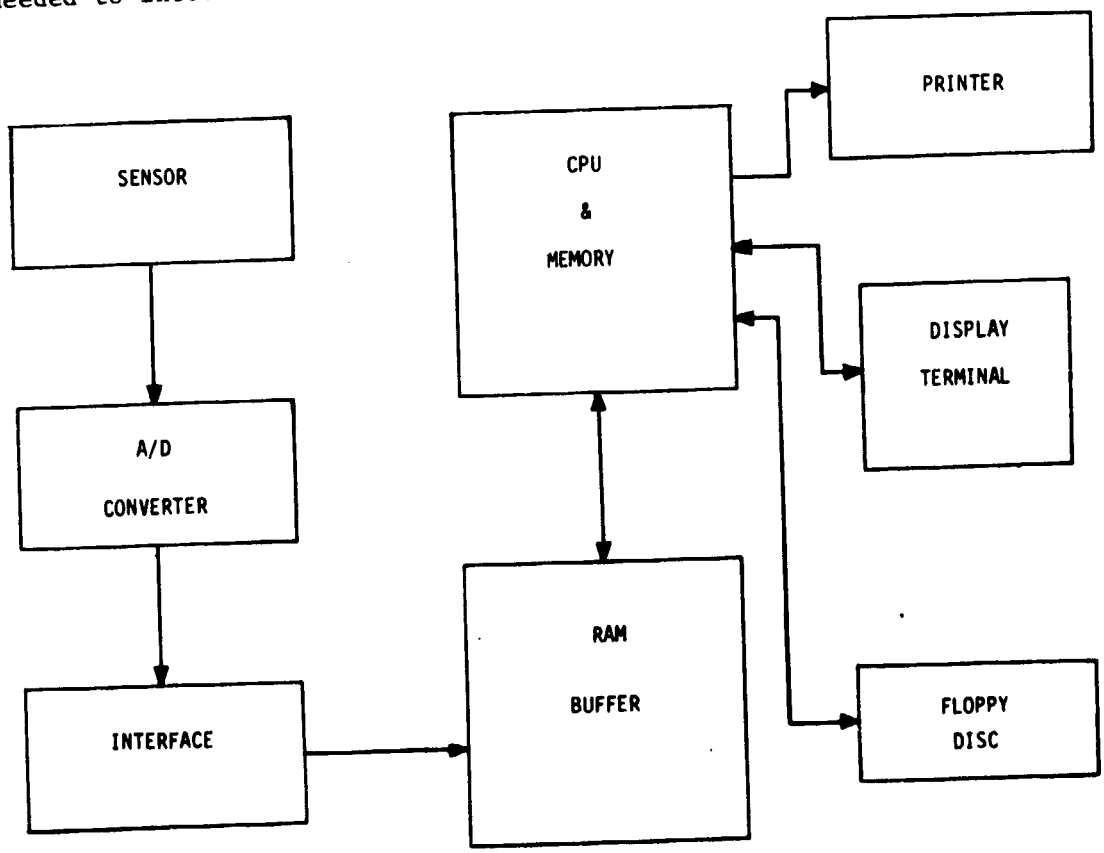

Figure 8-4. Breadboard System - Block Diagram

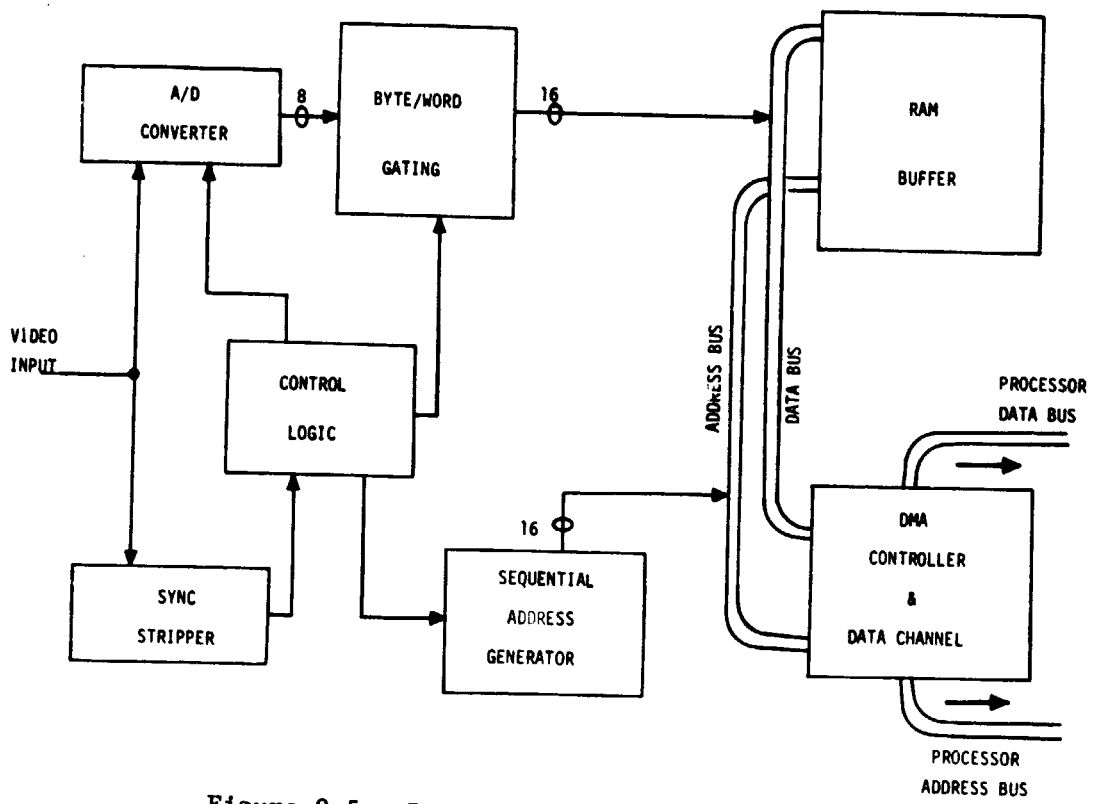

Figure 8-5. Breadboard System - Interface

To use the system for stand-alone program development (assembly, edit, debug, and listing), the operating system software, RTE-M, requires the display terminal and the floppy disk. The printer provides hard copy output for documentation and debugging. To use the system in the field requires the sensor, interface, buffer, and the display terminal. The algorithms and other programs are stored on floppy disk and are loaded into the processor memory after the system is set up at the test site. Traffic parameters measured at the test site can be stored on floppy disk in addition to being displayed to the operator. A preliminary comparison of some candidate minicomputer systems is shown in Table 8-1. The MIPROC-16 has the fastest instruction times but was quite poor on other factors. An additional 3 to 4 months of software and engineering time would be needed to do the job with this machine. The Varian V77-400 is the slowest of the three but is probably still fast enough. It has a dual port memory as an option but it is not fast enough to accommodate the high data rate from the sensor and an external buffer would still be required. Also, the software support for the small, stand-alone type of system needed for the breadboard was lacking, and total hardware costs would be higher than for the Hewlett-Packard system.

Other popular minicomputers from such manufacturers as Digital Equipment Corp. and Data General were dropped from consideration in

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Table 8-1. Preliminary Minicomputer Comparison

	HP 21MX-E	V77-400	MIPROC-16
Instruction times	2	3	1*
Memory cycle time	2	3	1
Dual port memory	No	Yes	No
Stand-alone assembly	1	2	No
System software	1	2	3
Hardware Interface	1	2	3
Overall Cost	1	2	3

*Rating of 1 is best.

preliminary screening. In almost every case, this was due to their high performance processors being designed to fit only into larger systems.

COST ESTIMATES

Any meaningful cost estimate should be prefaced by the assumptions made. These estimates are no exception. The basic assumptions here are

(1) A time frame: 1980.

(2) A production quantity: 100 units.

(3) A design architecture.

The costs are in dollars that an original equipment manufacturer (OEM) would expect to pay at the module or subassembly level. These costs are used because they are closest to available published prices. System assembly and testing costs would have to be added, but if the OEM doing the final assembly were also a major supplier of the components and subassemblies, these costs would be minimized. For example, manufacturers such as Texas Instruments or RCA are vertically integrated and could supply anything from the chip level to the completed system.

The design architecture assumes that the RAM buffer memory is integrated with the processor's main memory in a dual port configuration (as discussed above). Most of this memory system would be used as a full field buffer. The remainder would be used for working storage and data manipulation. All algorithms and programs would be stored in ROM memory. Communications circuits and servocontrol circuits would be integrated with the CPU electronics at the board level. Separate modems, for example, would not be required.

With these assumptions in mind, the following cost estimates were made:

Device	Cost
Microprocessor	$ 700
Memory, 32K words RAM	500
Program memory, 8K words ROM	200
A/D converter	150
Communications interface	200
Pan/tilt servo electronics	200
Power supply	200
Total	$2150

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SECTION IX

BREADBOARD ALGORITHM CONCEPTUAL DESIGN

In Section VI we discussed the various algorithm technologies and approaches which might be used to extract traffic information from real-time image data. It was concluded there that direct detection of traffic parameters rapidly becomes increasingly difficult as the distance between sensor and detection region increases. Therefore, for the conceptual design, we decided to pursue an algorithm which consists of two parts: (1) vehicle detection in the near field (100 to 200 feet (30.5 to 61 meters)), and (2) vehicle tracking of receding traffic to extend the capability of the sensor to acquire traffic information in the far field. The algorithm is labeled the Vehicle Detection and Tracking Algorithm (VDTA). The vehicle detection part could be applied to either on-coming, or receding traffic, but the tracking portion, of course, applies only to receding traffic.

Defining an algorithm to provide real-time extraction of traffic information is on the edge of capability for current technology, especially in view of the economic constraints of this application. Current technology basically can do simple scene analysis fast (e.g., change detection), or sophisticated scene analysis slow (e.g., artificial intelligence), or sophisticated scene analysis fast with special high cost devices. Analysis of real-time images for this application is complicated by a complex view geometry, highly variable objects to detect, highly variable background, signal degradation due to weather, and computation limitations imposed via cost constraints.

It should be noted that the VDTA defined in this section is only a conceptual design and is part of a feasibility study of a Wide Area Detector Sensor. The VDTA is by no means ready for operational application. Follow-up efforts of detailed software and hardware implementation, together with in-field experience would be required to assess operational readiness.

OVERVIEW OF ALL BREADBOARD ALGORITHMS

The VDTA is not the only algorithm needed in the WADS breadboard. The VDTA is a general preprocessing algorithm which reduces the image data to a representation in terms of vehicle descriptions and vehicle trajectories. Other less sophisticated algorithms can then be used to reduce the VDTA output to the desired specific traffic parameters. All the algorithms and their functional relationships are shown in Figure 9-1. The calibration algorithm provides a means of converting picture element locations to absolute locations on the road. A verification algorithm provides an automatic check of the hardware and software of the breadboard. In some applications the vehicle description and trajectory data of the VDTA may be sent over phone lines to an operation center for display, or further reduction. Alternately, a parameter reduction algorithm is used to convert the VDTA data to traffic parameters which

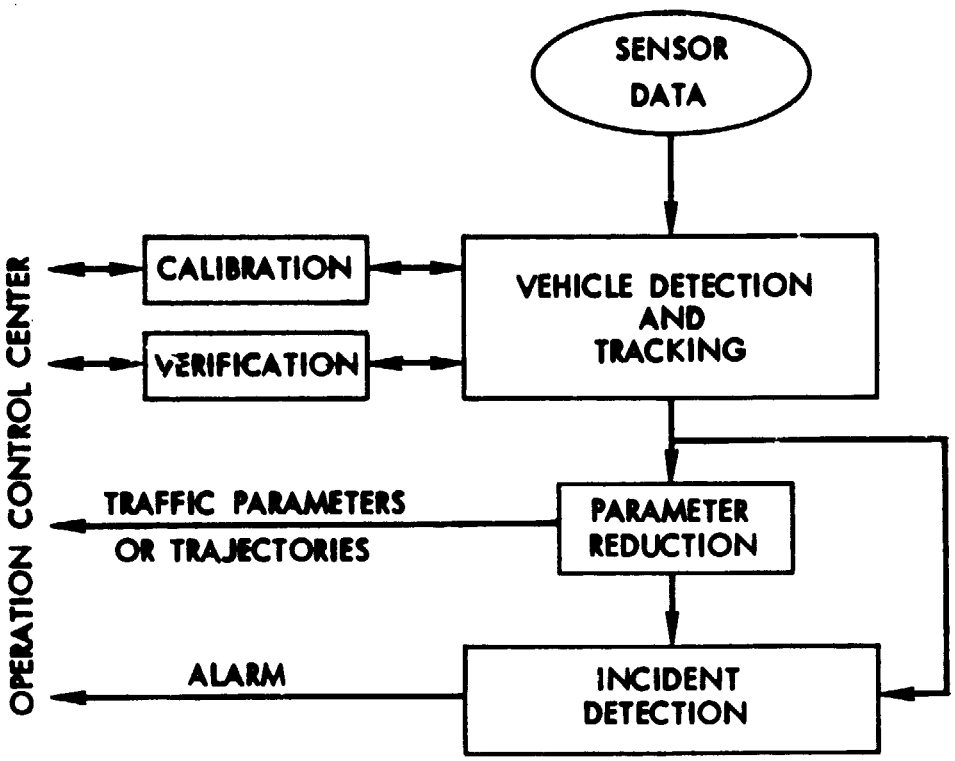

Figure 9-1. The Algorithms for the WADS Breadboard

are sent to the control center. An incident detection algorithm uses the resulting traffic parameters, and/or the VDTA output to make decisions regarding whether an incident exists or not. An alarm signal is sent when there appears to be an incident. Of all these algorithms the VDTA is the cornerstone and the most sophisticated. The general preprocessing of the VDTA provides an output which makes the definition of the parameter reduction and incident detection algorithms generally very simple.

THE CALIBRATION ALGORITHM

The purpose of the calibration algorithm is to enable conversion of the various picture elements of the image to the corresponding locations on the road. Consider the simple case where there is no skew or tilt in the road and the sensor configuration of Figure 9-2. Let h be the camera height, ϕ the vertical field of view, ψ the angle between vertical and start of field of view, r_v and r_h the vertical and horizontal resolution of the sensor, respectively, in terms of the number of digitized samples over the field of view. Let i and j be the line and picture element number from the sampled and digitized image with (i, j) = (1, 1) in the upper left corner of the image. Let x be the distance from the sensor along the ground corresponding to the center of the horizontal field of view. Let y be the distance along the ground

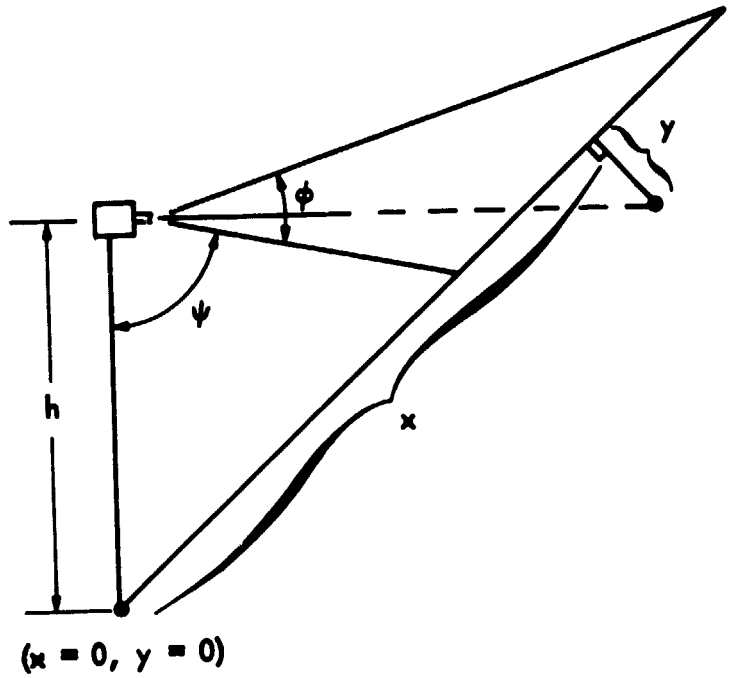

Figure 9-2. Simple Sensor Configuration

corresponding to the orthogonal distance from the above x axis. Then x and y in terms of i and j are

$$x = h \tan\left[\psi + \phi\left(1 - \frac{i}{r_v}\right)\right],$$

and

$$y = \sqrt{x^2 + h^2} \tan\left[\frac{4\left(j - \frac{r_h}{2}\right)}{3\, r_h}\phi\right].$$

Observe that one can now prepare a look-up table of values indexed on i and j as follows:

$$F_1(i) = h \tan\left[\psi + \phi\left(1 - \frac{i}{r_v}\right)\right],$$

$$F_2(i) = \sqrt{F_1(i) + h^2}$$

$$F_3(j) = \tan\left[\frac{4\left(j - \frac{r_h}{2}\right)}{3\, r_h}\, \phi\right] .$$

Then for any value of (i,j) one can quickly calculate the corresponding ground location by using the look-up tables and

$$x = F_1(i)$$

$$y = F_2(i) \cdot F_3(j) .$$

This simple example demonstrates the technique for quick conversion of (i,j) to (x,y) without a look-up table location for every picture element. Note that the functions F_1, F_2, and F_3 need to be computed once at set-up of the sensor and not during operation of the sensor. In the general sensor configuration there may be skew or tilt of the road and the expressions become more complex, but the same approach applies.

The procedure for calibration is one of inputing to the WADS breadboard at set-up time the necessary inputs for calculating the look-up table discussed above. This procedure is depicted in Figure 9-3. At set-up time a range finder is used to identify ground distances corresponding to a number of picture elements denoted on a monitor display by a cursor. The calibration algorithm of the breadboard would use these inputs to estimate the sensor configuration and prepare the look-up tables. A cursor, or light pen method would also be used to input other information such as lane locations, and regions in the image for vehicle detection. The calibration algorithms are only run during set-up, not during operations so they are not computation limited. In a difficult sensor configurations a piecewise fit of the road surface is even feasible.

THE VEHICLE DETECTION AND TRACKING ALGORITHM

Overview of the VDTA

A block diagram of the VDTA is shown in Figure 9-4. The functions are divided into detection, description, and tracking. The left side of Figure 9-4 shows the functions of detecting a vehicle, obtaining a description of the vehicle, and initiating tracking. These functions are to be performed entirely in the near field, as close as possible

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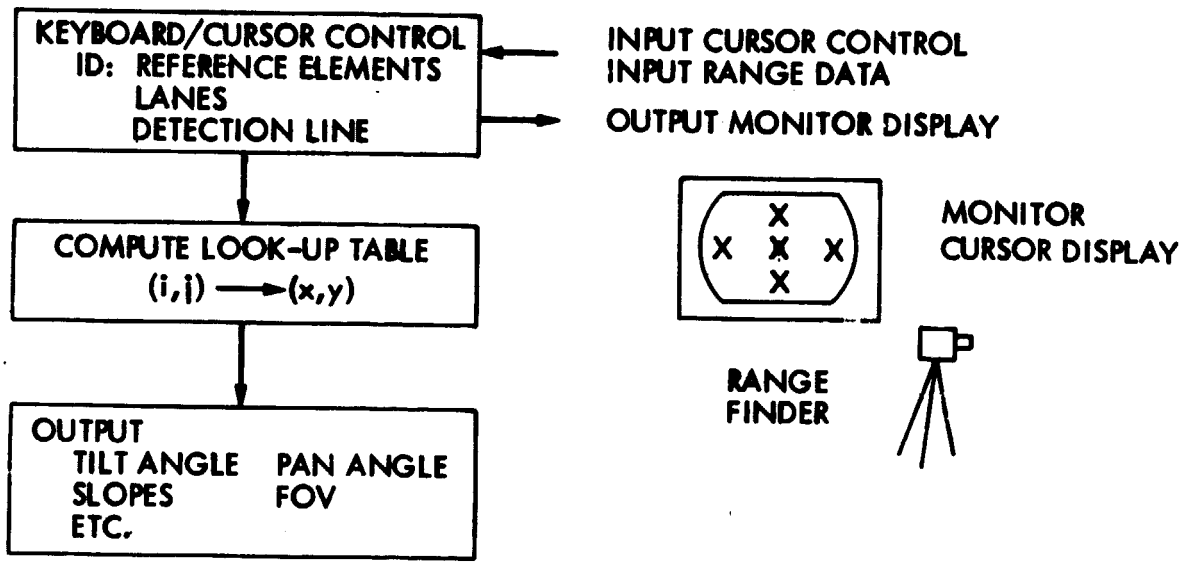

Figure 9-3. Calibration Procedure

to the sensor consistent with constraints of sensor optics, etc. In the near field one has the advantage of less vehicle merging and higher resolution. Acquiring initial information in the near field, simplifies the obtaining of information in the far field. In Group B the vehicle positions are periodically updated as the vehicle proceeds into the far field. Thus, the output from Group B is trajectory information on all the vehicles.

Detection of Vehicle Vs. Road

Even in the near field the reliable detection of vehicle vs. road is not simple. This is due to the large differences in vehicles, changing background, shadows, merging and lane overlapping views of vehicles, and wide variations in velocity. The road also provides a widely varying background; however, it does not change rapidly. Therefore, it is easier to detect road vs. not road as opposed to attempting to directly detect the vehicle.

For simplification the following discussions will address a single lane, although the algorithm would actually address all lanes jointly. The near field detection of not road is done for a single sense line across the lane as shown in Figure 9-5(a)-(d), where various not road objects are depicted approaching the sense line. The sense line is

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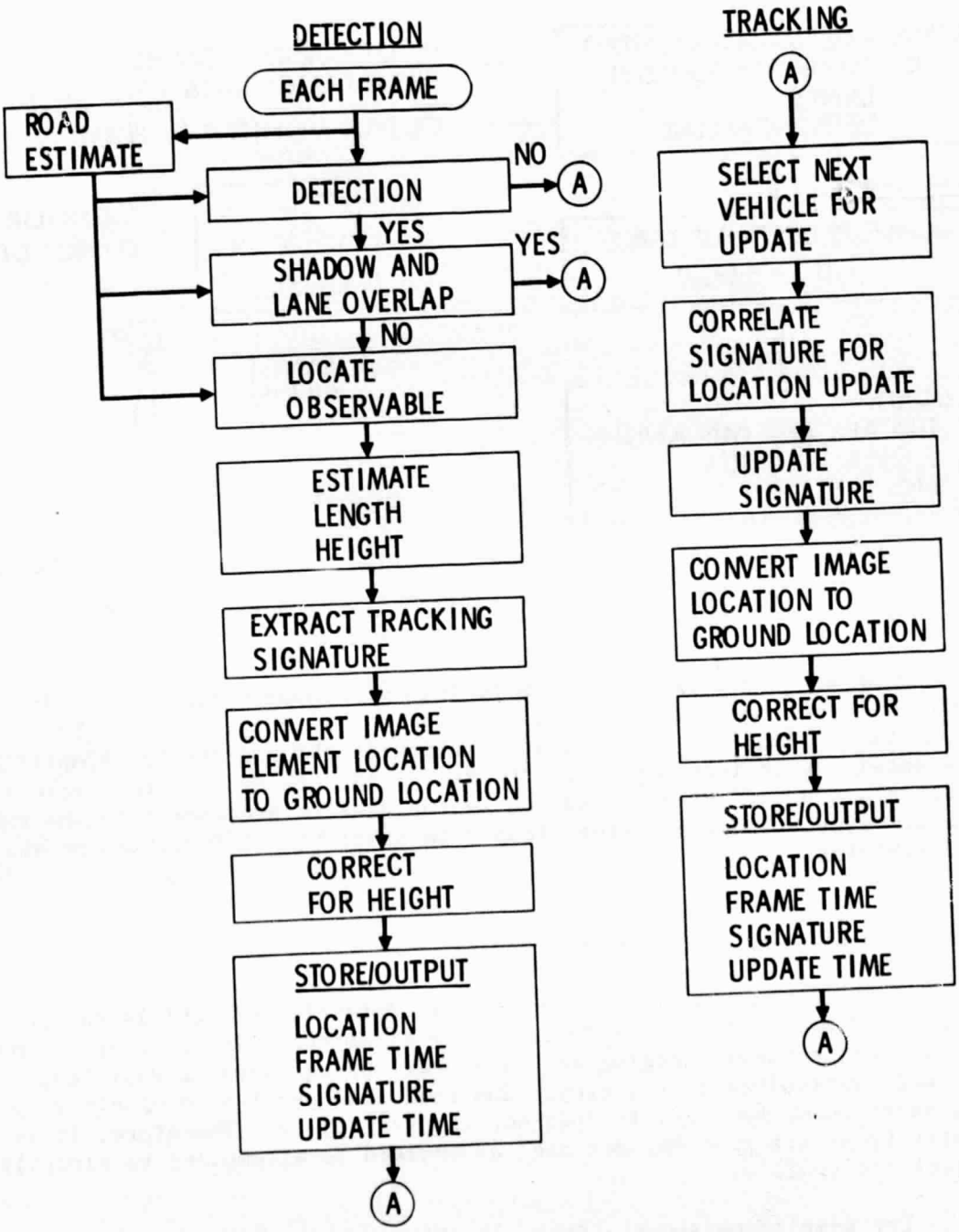

Figure 9-4. Vehicle Detection and Tracking Algorithm

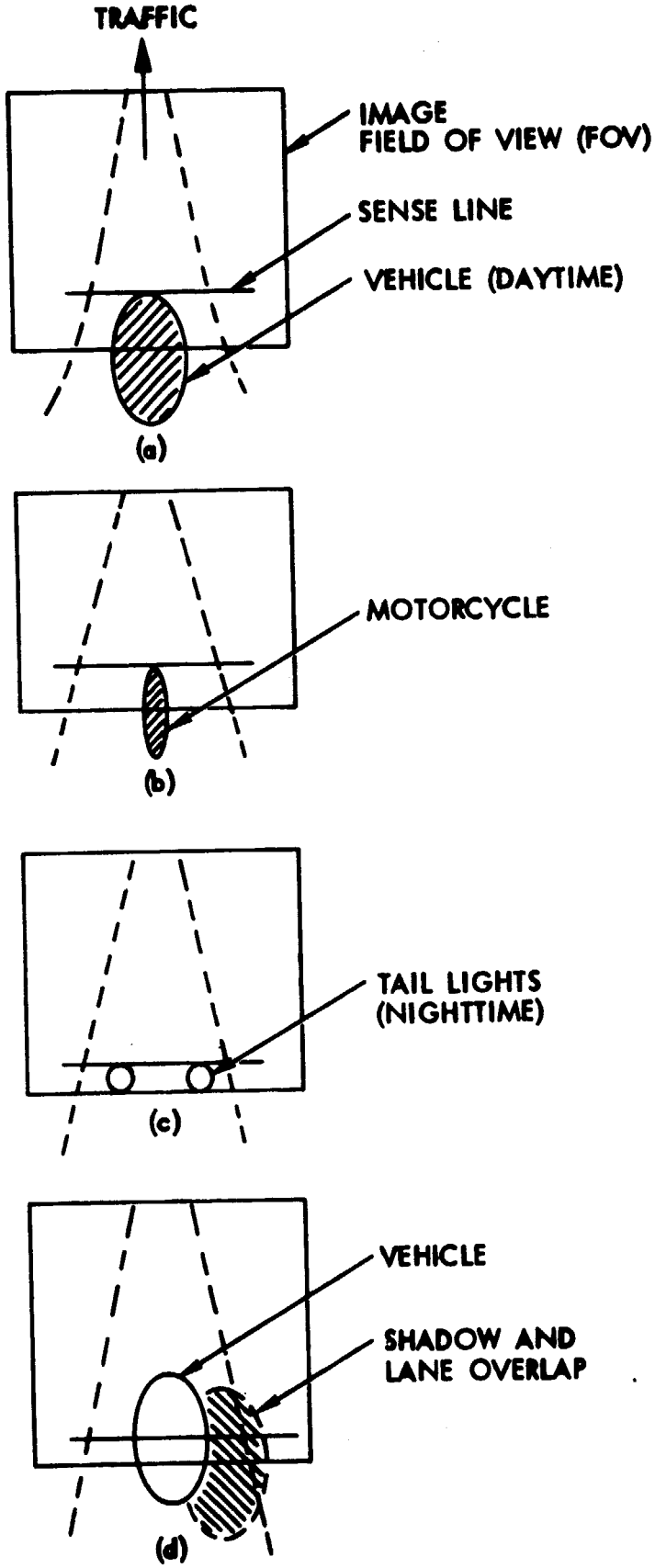

Figure 9-5. Sense Line Location and Various Non-Road Objects

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simply a subset of image elements selected from a full field buffer containing the 240 x 256 image elements generated by the sensor. The field of view (FOV) of the image is represented by the box in each figure. Note that the sense line is positioned very close (within 10 to 20 elements) to the bottom edge of the image (near field).

Now consider the adaptive estimator for the road. At each frame time (30 frames/second), the samples of the sense line are acquired. The samples are first compared with sense line samples from other recent frames to detect motion. If motion is detected, then the sample does not represent road and is not used by the road estimator. If little, or no motion is detected the samples are used to update the road estimator. Actually, the samples may correspond to a very slow, or stopped vehicle. Therefore, the road estimator is updated (changed) very slightly from its current value in any frame time. Thus the road estimator will track gradual changes in the road, but be affected very slightly due to moving vehicles. If a vehicle actually stops on the sense line it will eventually be used for a road estimate, but then this situation inherently corrects itself when the vehicle begins moving again (furthermore, the tracking part of the algorithm identifies the vehicle as nonmoving).

Once an estimate is available of the road (at the sense line), then detection of not road is very simple. The sense line samples of each frame are simply compared to the road estimate, and if the difference exceeds a threshold it decides not road, and otherwise road. The difference measure is similar to the Euclidean distance and it is implemented via a table look-up for the square function.

Locating Vehicle in the Cross-Lane Direction

In Figure 9-5(d) is shown an example of a shadow, or vehicle overlap from an adjacent lane. Such an object would be detected as not road. Therefore, at the same time the difference between sense line samples and road estimate is computed, we also calculate two other simple features. The first feature is the first and last elements of the run of sense line samples which correspond to not road. These points indicate the boundaries in the cross lane direction for the not road object. The second feature measures the discontinuity and local average level in the not road samples to discriminate between vehicle and vehicle shadow. Then both of these features are individually obtained over successive occurrences of not road detections for the sense line. These features give a rough estimate of the vehicle boundaries in the cross-lane direction (even if in-between lanes). Locating the vehicle in the cross-lane direction is important in view of the many possible variations of vehicles as demonstrated in Figure 9-5(a)-(d). Furthermore, it is necessary to limit the analysis of the along-lane direction only to the regions necessary as indicated by vehicle presence and vehicle cross-lane boundaries. The previous establishment of a road estimate made the calculation for the above features simple and more reliable.

Locating Vehicle in the Along-Lane Direction

In Figure 9-5(a)-(c) are shown the widely different type of observable patterns which occur due to vehicles. The advantage of a cross-lane sense line is that very few samples need be used to detect road, or not road regardless of the shape of the vehicle. Note that this is true even for the essentially bright point source of a taillight. Even though the taillight may be moving 10 lines per frame, the sense line elements are integrating continuously during the frame period, so the passage of the taillight is detectable. On the other hand, as discussed in Section VI, Feature Extraction Techniques, a cross-lane sense line is far inferior to an along-lane sense line for measuring position along the lane. Furthermore, a road estimate for an along-lane sense line would greatly assist estimation of vehicle length, and along-lane position. But, of course, we cannot afford to establish a road estimate for all possible along-lane sense lines which might be required by different vehicles. Therefore, the following approach is used. During the comparison of the cross-lane sense line with the road estimate, we also search for the location of maximum difference. Then upon the first occurrence of a not road decision, an along-lane sense line is accessed from the buffer as shown in Figure 9-6, at the cross-lane position corresponding to maximum difference from road. This along-lane sense line now serves as a road reference for the portion of the sense line in front of the vehicle. At the next frame time, the same along-lane samples are acquired and subtracted from the previous frame samples. The difference between successive frame samples will be near zero for the road, and larger for the vehicle. Thus, for simple computation the vehicle was located across the lane, and then the successive along-lane sampling is used to more accurately measure the vehicle (object) front edge. A similar procedure is used after the last not-road detection in order to identify the back edge of the vehicle. These measurements are important for measuring length, initial velocity, and height of vehicle. Initial velocity is best determined by observing the back edge of the vehicle, since this edge is nearest the road. Length is needed for occupancy measurements, and a height estimate is needed to correct estimates of location and velocity. Furthermore, identifying an along-lane position of the vehicle avoids confusion when vehicles slow, or stop over cross-lane sense lines.

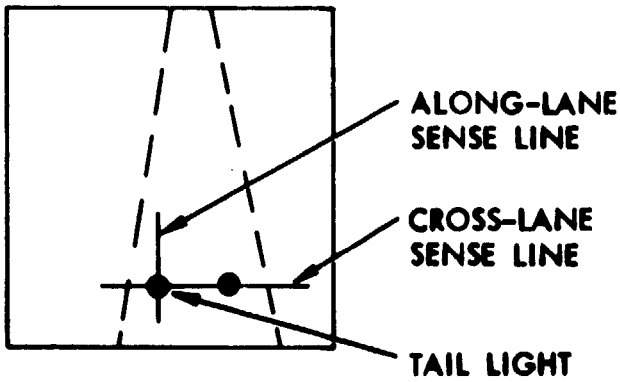

Figure 9-6. Along-Lane Sense Line

Vehicle Length and Height Estimates

Vehicle length is needed to compute occupancy, and the length of a vehicle observed in a WADS image sensor is dependent on the vehicle height. Section VI, Vehicle Length and Height Estimation, analyzed the sensitivity of the length estimate to errors in measuring vehicle height. Also note that the signature of the vehicle which will be tracked must be derived from the top of the vehicle to minimize the impact of vehicle occultation in the far field. But the ground location corresponding to this signature (vehicle) is determined from the image and is affected by the height of the signature. Therefore, a rough estimate of vehicle height is helpful in improving the accuracy of location and velocity estimates for the vehicles being tracked in the far field. Refer to Figure 9-7. The observables in the image are d_1, d_3 and d_1', d_3'. The location of d_2 in terms of H and d_3 is

$$d_2 = \left(\frac{h - H}{h}\right) d_3 .$$

Assume the velocity of the vehicle is constant over the measurement interval, then

$$d_1' - d_1 = d_2' - d_2 = \left(\frac{h - H}{h}\right)\left(d_3' - d_3\right) ,$$

and vehicle height is given by

$$H = h\left[1 - \frac{(d_1' - d_1)}{(d_3' - d_3)}\right] .$$

The vehicle length is then given by

$$L = d_2 - d_1 = \left(\frac{h - H}{h}\right) d_3 - d_1 = \frac{d_1' d_3 - d_1 d_3'}{d_3' - d_3} .$$

Initial Signature Extraction

The along-lane sense line provided an initial location for the vehicle, but this approach is not adequate for following the vehicle in the far field due to possible merging in the image with another vehicle. Thus a tracking algorithm is used to follow the vechile. The previous initial along-lane positioning, however, assists the signature extraction process, since the scene has already been segmented into moving

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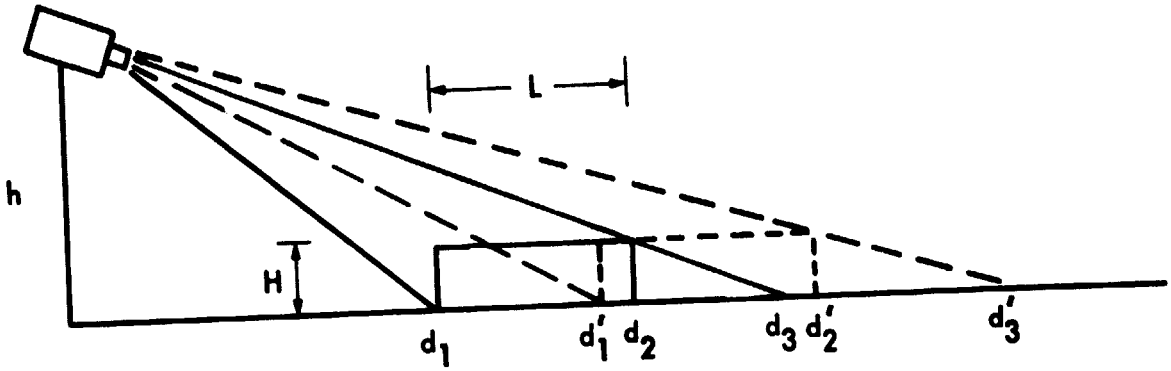

Figure 9-7. Successive Views of Vehicle Length L and Height H

and non-moving parts. The signature is extracted from the portion of the along-lane sense line which contains the vehicle. In order to reduce computation in the correlation tracking, the signature is limited to about 10 to 20 samples. A simple search of the along-lane sense line is used to select key element locations, such as maximum, minimum, and maximum slope locations. These sample locations provide a subset of elements which tend to have good autocorrelation properties.

Convert Image Element to Ground Location and Correct for Vehicle Height

The vehicle location must repeadably be determined. The relationship between image element and ground location is a complicated function of sensor location, view angle, slope of the road, etc. This was discussed previously in Section IX, The Calibration Algorithm, where it was shown a simple look-up table computation could give the ground location for any picture element. This vehicle location would then be corrected to account for the vehicle height by multiplying by (h - H)/h. This correction factor applies for both the x and y components of the vehicle location.

Signature Correlation and Update

The vehicle is followed into the far field via correlation tracking. The update interval for each vehicle is about every half car-length or less in the image. Thus very little searching is required by the correlator. This is especially true, since over such short distances the bounds on acceleration of vehicles imply the new position of the vehicle cannot vary much from the predicted position. The correlation is over about 10 points and 10 positiions. It also follows the gradual cross-lane motion associated with lane changes. Correlation processing is the primary computation hurdle in this algorithm, because of the constraints of the breadboard computation limitations, and no use of any hardware special processors.

The signature of the vehicle changes size and even possibly shape as the vehicle recedes. This can be handled by doing the correlation in terms of ground distances, but that would require constant conversion between image elements and ground location. Rather we note the signature changes very slightly per update, so the changes per update can be ignored. But in order to track the gradual large changes, the signature is updated every time the vehicle location is updated.

THE PARAMETER REDUCTION ALGORITHM

Given the trajectory of the vehicles, the breadboard can easily compute average traffic parameters for selected time and space intervals. There is great flexibility in what parameters can be computed from the VDTA output. The computation load of this algorithm is expected to be relatively small. Note that the entire vehicle description and trajectory information could also be sent over phone lines to the Operations Center.

THE INCIDENT DETECTION ALGORITHM

The incident detection algorithms automatically detect conditions indicating an incident. In existing traffic monitoring systems, incident conditions have always been determined from a very limited number of summary traffic parameters; however, with the WADS sensor there is also the ability to use the entire information of traffic flow contained in the VDTA output. This should provide interesting and useful new results in incident prediction and detection.

THE VERIFICATION ALGORITHM

The verification algorithm provides an automatic check of the breadboard hardware and software. For example, samples of digitized image features corresponding to known situations can be stored and used as simulated input to the various algorithm computation elements. Videotape image sequences of known traffic conditions can be input to the breadboard for verification. The verification algorithm can also provide for display of the VDTA outputs to enable direct observation of the vehicle detection, description, and tracking operations. While the WADS sensor is more complex than current traffic sensors, its increased capabilities can also be used to highly automate the task of making sure it is operating properly.

SUMMARY OF BREADBOARD ALGORITHM CONCEPTUAL DESIGN

Although there are many separate functions within the VDTA, all of the repetitive computation is very simple in nature. Many of the separate features used are generated simultaneously with one pass through the data. The VDTA requires the access and processing of only very small subsets of the total image. Another important factor is that as the

number of vehicles increase, the average speed of the vehicles decreases, keeping the detection and tracking update computation in reasonable limits. The breadboard minicomputer will provide adequate performance for implementing the VDTA. Although much higher instruction rates are available, the breadboard minicomputer offers a good trade-off of speed, cost, and software support for flexibility. Simulations were conducted of the detection portions of the VDTA in real time, and on the tracking portion in non-real time. These simulations indicate good performance is feasible, but the limitations from bad weather and occultation in the far field need experimental determination with a breadboard model.

SECTION X

CONCLUSIONS AND RECOMMENDATIONS

The results of this analysis indicate a WADS is feasible and potentially very beneficial for traffic control. A standard television image sensor was determined to have adequate resolution and sampling rate to provide for incident verification and automatic traffic monitoring. While an infrared image sensor is somewhat preferable it is too expensive compared to the visual television sensor. The memory and computational hardware is readily available and adequate for WADS, but the requirements of WADS for practical image processing is at the edge of the current state of the art.

The production WADS is expected to consist of a CCD image sensor and a microprocessor. The WADS breadboard is recommended to consist of a standard Vidicon television camera and a minicomputer in order to provide more flexibility and software support during the breadboard testing phase. The proposed image processing algorithm for WADS centers around a Vehicle Detection and Tracking Algorithm which reduces the image data to vehicle descriptions and trajectories. This processing approach makes full use of the power of an image sensor, but in a manner convenient for a traffic engineer to apply.

The combination of hardware and processing conceptually designed for WADS was shown as capable of providing a significant improvement over existing traffic monitoring capabilities and potentially at a lower total sensing system cost. However, more information is yet required concerning the occultation limitations caused by the view geometry, and the limitation of bad weather conditions. Also additional analysis is required for a better assessment of the impact of WADS on a total traffic monitoring and control system. At this time we highly recommend continuing into the breadboard phase of this work.

SECTION XI

DESIGN REVIEW ACTIONS

After the conceptual study was completed, a design review was held at FHWA's Fairbank Highway Research Station on April 28, 1977. The results were presented and many important comments were received. In addition to the FHWA reviewers, three outside experts participated in the design review. Each expert represented a field of key importance to the WADS project: image sensor technology, image processing technology, and freeway operations (the eventual WADS user community). Besides the verbal comments made at the meeting, these outside experts summarized their comments in letters written to the FHWA Contract Manager after the review.

The review continued all day, with presentations of all of the key results documented in the earlier sections of this report. In the course of the review several questions were raised and observations made that merited further study and analysis. The details of this post-review activity are incorporated into the earlier sections of the report in their appropriate places.

There was general agreement that the review was well executed and worthwhile for all who attended with high participation and good, constructive criticism being offered. The consensus among those attending was that the work is comprehensive, promising, and merits continuation. A summary of the major points of concern raised in the review and the authors' responses as indicated (including post-review study) are given below.

(1) Concern: "Even though this is a research project, it should be kept in mind that the eventual goal is a WADS system that will be simple, inexpensive, and dependable working in the field environment. It should also do a better job than current detection systems. There is a need for a comparison of WADS and other detection systems, both functionally and economically."

Response: The goal as stated above has always been important in the design team activities. The team also recognizes the importance of the economics of a new technology in the decisions of operations personnel who will purchase it. A comprehensive appraisal of WADS and other detection systems regarding performance and cost should be made. This should be done, however, after an adequate assessment has been made of the algorithm capabilities and the amount of sensor hardware needed for the job. The breadboard should contribute greatly to the needed information in this area.

(2) Concern: "Making a single sensor have two operating modes - traffic measurement and operator-controlled pan/tilt/zoom - creates several areas of concern: (1) the loss of traffic data while in the second mode and (2) the realignment needed

when returning to the measurement mode (is it really a repeatable position?). Associated with this latter concern is the need for recalibration of the sensor if repositioning is not accurate enough. Why not have two cameras, one fixed and one movable, and alleviate these problems?"

Response: It turns out that either of the two above modes is technically and economically feasible. However, the two-camera approach does appear more favorable. As explained in this report, the cost of an extra fixed position camera is estimated to be only several hundred dollars more than the added cost of augmenting a pan/tilt/zoom device with sufficiently accurate repositioning (1980 production costs). The advantages of the two camera approach are: (1) ability to obtain traffic data simultaneously during pan/tilt/zoom operation, (2) elimination of small errors introduced by the repositioning mechanism, and (3) increased reliability by eliminating the more complex mechanical repositioning device (the extra camera is solid state technology). Finally, it should be observed that in the long term the costs of the extra camera will be rapidly decreasing, while the same is not true for the repositioning pan/tilt/zoom mechanism. Since the two camera approach is clearly preferable and also likely to be lower in long term cost, the two camera mode is recommended for the production WADS. For the WADS breadboard the focus of the effort is on measuring traffic data via a dedicated camera. The simple pan/tilt/zoom mechanism is a technology which does not require further investigation for this application. Therefore, the WADS breadboard will use a camera which can be manually oriented to any desired fixed position and zoom.

(3) Concern: "Is the pan/tilt/zoom function really needed? Won't the camera be damaged by looking into the sun?"

Response: In the view of the freeway operations personnel interviewed, effective incident management depends on rapid diagnosis of the nature of the incident so that the appropriate type of vehicle can be dispatched. A fixed-view camera looking over a quarter-mile section of freeway is inadequate to perform the diagnosis function. The standard vidicon camera would be damaged if accidently pointed at the sun. For this reason the silicon-diode array vidicon sensor will be used on the breadboard. Both the silicon-diode array vidicon sensor to be used on the breadboard, and the CCD sensor expected to be used on the production WADS are not damaged by accidental pointings at the sun.

(4) Concern: "WADS will place considerable computing capability at field sites. Why not use it to do other jobs in the field, like ramp control?"

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Response: This is a very good idea. There is no reason why excess processor capacity could not be used for other jobs. When the WADS project moves into a "commercialization" phase this asset should be explored and developed.

(5) Concern: "How will pole sway by wind or vibration affect the sensor?"

Response: Motion of the sensor is of concern in that if it becomes too large it will interfere with the algorithm for acquiring traffic data. The sensor motion can first be separated into translational and rotational components. The "worst case" motion encountered by the WADS is the rotation resulting from a pole mounting. The significant rotation components are due to (1) twisting about the pole axis, and (2) rotation about the axis along and across the direction of view caused by the slight camera tilting as it transverses a portion of an approximate circular arc during the swaying of the pole. Of these components the rotation about the pole axis is generally much smaller. Thus, the main concern of sensor motion is due to rotation caused by wind-induced pole deflections from the vertical position.

Typical "worst case" deflections for the WADS application are 1/2 to 1-inch (1.3 to 3.8 cm) deflections for a 25-foot (7.6-meter) pole, and 1 to 2-inch (2.5 to 5.0-cm) deflections for a 50-foot (15.2-meter) pole. Although the deflection of the higher pole is larger, the resulting rotational component is about the same for the 50-foot (15.2-meter) pole as for the 25-foot (7.6-meter) pole. This is due to the larger radius for the larger pole. A 1 to 2-inch (2.5 to 5.0-cm) maximum deflection results in a peak shift of the entire image by 1 to 2 picture elements (for a sensor with a 48° field of view and 240 resolution elements). These peak shifts have a very small impact on the algorithm for traffic measurement. Furthermore, the small instantaneous errors generated by the motion are further reduced through subsequent averaging. Finally, observe that the above impact was assessed for extreme wind conditions. Therefore, it appears that WADS should not be significantly affected by vibration or pole sway.

(6) Concern: "The cost estimate for the production sensor seems high because of the overheads put on the materials costs. This should be reexamined."

Response: The cost estimate has been revised accordingly.

(7) Concern: "The presentation stressed 25-foot (7.6-meter) mounting heights. What are the benefits and costs of higher mounting for the camera?"

Response: The choice of 25 feet (7.6 meters) was made because that would be a mounting height conveniently available in the right of way - such as sign bridges, overpasses,

sign mast arms and the like. As seen in the report, the benefits of higher camera mounts are (1) improved viewing position for incident verification and visibility to the opposite side of the freeway traffic flow, (2) a more perpendicular view of traffic in the near field, which enables higher occupancy conditions before needing to contend with merged vehicles, and (3) more uniform and efficient use of the available sensor resolution through the observed test strip. Note that the increased swaying of the 50-foot (15.2-meter) pole is not expected to cause a problem. The disadvantages of the higher pole are (1) increased expense (both first cost and maintenance), and (2) more adverse environmental impact. The extra height in general does provide significant advantages to the algorithm for traffic flow measurement, and also for incident verification. However, it does not appear essential for either function. The final decision on mounting height is a cost vs. benefit trade-off which likely will also depend on specific location, and a decision should be made after the breadboard phase is complete, when the technical performance of the sensor is better understood.

(8) Concern: "The choice of charge-coupled-device (CCD) technology for the production sensor is good. Using an antimony trisulfide vidicon for the breadboard is not a good selection because its spectral response is different than a CCD sensor, and because it is damaged when pointed at the sun."

Response: The silicon-diode array vidcon is a better choice for the breadboard, since it corrects the above deficiencies and costs only a few hundred dollars more than the standard vidicon sensor. We will use a silicon-diode array vidicon in the breadboard.

(9) Concern: "Do not underestimate the development task ahead, particularly in the image processing software area. Many details must be worked out, such as the calibration procedure and tracking performance in difficult conditions. In particular, the detection and tracking performance in high density traffic (merged vehicles), are examples of particular concern."

Response: We are in complete agreement with the above concern.

(10) Concern: "How will the WADS recover from a power failure?"

Response: There are several adequate solutions for this problem. Basically, the program and calibration information of WADS is stored in a memory which is not lost during a power outage. Upon return of power, the processor begins execution, at a prespecified location of this memory, to implement a restart of the detection and tracking algorithm. The WADS

program would be stored in Read-Only-Memory (ROM), and the location calibration data would be stored in either a Complementary Metal-Oxide Semiconductor (CMOS) memory with Nickel-Cadmium (Ni-Cd) battery, or a Metal Nitride-Oxide Semiconductor (MNOS) memory (1980 time period). Each of these techniques should enable the WADS to properly restart entirely on its own after power is restored. The impact on production cost, for this capability, is insignificant.

(11) Concern: "More work needs to be done on the WADS design for the field environment. How will the lens be kept clean? What is the maintenance plan?"

Response: These are very important questions for the "product engineering" of WADS. These issues will be addressed after the breadboard has shown that the image processing concept is sound.

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APPENDIX A

FEDERAL HIGHWAY ADMINISTRATION DEPARTMENT
OF TRANSPORTATION

No. WADS-100B
20 March 1977

FUNCTIONAL REQUIREMENT
WIDE AREA DETECTION SENSOR

Prepared by
JET PROPULSION LABORATORY

1.0 SCOPE

This document establishes the functional requirements of the Wide Area Detection Sensor (WADS) primarily intended for the measurement, collection, and transmission of limited access highway traffic parameters and the remote observation of these highways by means of visual images.

2.0 APPLICABLE DOCUMENTS

Pub. No. TS 1-1976, "Traffic Control Systems," National Electrical Manufacturers Association.

3.0 FUNCTIONAL DESCRIPTION

3.1 General

The primary function of the WADS is to measure certain traffic parameters of limited access highways by observing the lanes in one direction and to transmit these measurements to a central location. The secondary function of the WADS is to perform as a remotely controllable image sensor which will provide visual observations of the highway to operators at the central location.

3.2 Traffic Parameter Objectives

The general objective of the traffic parameter measurement function is to provide continual and accurate information in near "real time" to the central location concerning the vehicle flow, as measured, in each lane.

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3.2.1 Parameter Measurements

The parameters to be measured directly in each lane are vehicle count, speed, and presence.

3.2.2 Test Section

The parameter measurements are to be made over a test section which is an established distance (cf Para. 5) nearest to the sensor as per Figure 1.

3.2.2.1 Speed

Speed shall be measured for each vehicle in each lane. The speed measurement shall be the space mean speed measured over a known distance.

3.2.2.2 Vehicle Count

A count of each vehicle passing arbitrary fiducial line(s) in the WADS field of view shall be accumulated for each lane. Figure 1 depicts the possible position of these lines in the image view.

3.2.2.3 Vehicle Presence

The vehicle presence of each lane shall be determined by measuring the accumulated time that vehicles are present on and/or traversing the fiducial line(s) in the Test Section.

3.2.3 Derived Parameters

Other traffic parameters, such as density and occupancy, and the averages and accumulations of measured parameters shall also be provided.

3.2.3.1 Occupancy

The occupancy of each lane shall be provided. Occupancy is defined as the ratio of vehicle presence time to the total time expressed as a percentage.

3.2.3.2 Density

The density of each lane in vehicles per mile shall be provided. Density shall be determined from either counting the vehicles entering and leaving or by direct observation of the Test Section.

3.2.3.3 Averages and Accumulations

Continuous and short time averages of the measured lane parameters and occupancy shall be determined. The short time averages shall be accumulated from periods of 15 seconds to 15 minutes as commanded from the central location. The time need not be the same for each parameter. Accumulations of lane parameters summed over commanded lengths of time shall also be determined.

3.3 Imaging Objectives

Images of the highway and traffic conditions are to be provided to the central site on command. The central site observer should have immediate control over the directivity, viewing angle, and image forming functions of the image sensor. The images are to be of sufficient resolution to allow an operator to make gross estimates of the traffic condition and observe and discern individual vehicles at the maximum range.

3.3.1 Directivity

The imaging sensor shall be equipped with electromechanical pan and tilt mechanisms which shall move the sensor to the desired direction for viewing.

3.3.1.1 Pan

The image sensor pan mechanism shall allow the camera to slew and point in any direction in azimuth.

3.3.1.2 Tilt

The image sensor tilt shall be capable of directing the aiming point of the sensor to above the horizon to well below the horizon regardless of the azimuth direction.

3.3.1.3 Home

A positively indexed home position shall be provided to return the image sensor to the position used for traffic parameter determinations.

3.3.2 Viewing Angle

The viewing angle of the image sensor shall be continuously variable and determined by operator control. The horizontal included view angle tangent shall be variable over a six-to-one range. The vertical angle shall be 3/4ths the horizontal angle. The required variation in magnification of the image to achieve the view angles shall be accomplished before the image is formed on the sensor and no vignetting shall be allowed to restrict the view angle nor electronic "magnification" used to achieve apparent telephoto effect.

3.3.3 Image Forming

The image forming functions which can be varied to accommodate changing light levels and image sharpness (e.g., aperture and focus) at the desired viewing distance shall be under immediate operator control.

3.4 Functional Elements

The WADS should consist of: an image position control subsystem with associated positioning mechanism; an image forming subsystem to

accomplish various image magnifications, view angles, and to accommodate various lighting levels and distances; a data accumulation and signal conditioning subsystem to collect and codify the information signals from the image sensor; a processor subsystem which will extract, accumulate, and organize the desired traffic parameters and accept and interpret image sensor and processor commands from the central location; a communication interface subsystem which will connect to common carrier or dedicated communication links (e.g., microwave, broadband land lines, data lines, etc.) and transmit the parameters and images to central location and also receive commands and signals from the central location; and the necessary power, timing, and synchronizing circuitry to allow each subsystem to properly perform. These elements are depicted in Figure 2.

4.0 INTERFACE DEFINITION

4.1 Electrical Interfaces - General

Electrical grounding, electrical bonding, electrical interface circuits, and electromagnetic compatibility requirements shall be in accordance with comparable requirements stated in NEMA Specification TS 1-1976 Traffic Signals and Controllers.

4.2 Power

4.2.1 The prime power for the WADS shall be derived from a single phase 117 volt 60 Hz 20 ampere service drop.

4.2.2 Power Subsystem

All voltages, either AC or DC, needed for the various WADS subsystems shall be derived from a power subsystem. The power subsystem will isolate failures in the various subsystems to prevent a power related failure in one from affecting the others.

4.2.2.1 The frequency of the prime power source shall be monitored and out of tolerance occurrences indicated through engineering telemetry.

4.2.2.2 The power subsystem shall furnish voltage and current test points for determination of proper operation.

4.3 Input Signals

The input signals to the WADS are those commands and program changes from the central location.

4.3.1 All input signals should be of the same type and be accommodated on the same input line pair.

4.3.2 All input signals should be in the same format.

4.3.3 The input signal line pair should provide means of locally inserting test signals for the purpose of on-site maintenance.

4.4 Output Signals

The output signals from the WADS are the traffic parameters; measured, derived, averaged and accumulated; the image representation; and the necessary engineering telemetry measurements of internal WADS conditions needed to establish that proper operation is maintained.

4.4.1 The output signals representing traffic parameters should be of a uniform format assembled in a message containing sufficient identifiers to allow the central location to properly interpret the message.

4.4.2 Engineering telemetry messages shall be similarly arranged in standard formats and arrays.

4.4.3 Parameter and telemetry messages shall be organized to be sent as packet messages to the central location either on demand or in a prearranged or commanded sequence.

4.4.4 The messages from the several WADS sharing a communication link shall be time division multiplexed.

4.4.5 The image message shall be in a serial or serial-parallel form using as many communication lines as necessary concomitant with the image rates and resolutions.

4.4.6 The transmission of image messages shall not preclude the nearly simultaneous transmission of parameter and telemetry messages and the receipt of commands of a WAD.

4.5 Mechanical Interface

4.5.1 General

The image sensor is intended to survey as much of the highway as practical and should, therefore, be located in a position high above the roadway to obtain a clear view. The remaining functional elements should be available for easy access for maintenance and periodic inspection. Separate requirements are therefore necessary for the imaging and electronic functional subsystems.

4.5.2 Imaging Subsystems

The imaging subsystems include the image sensor, image forming devices, and directive mechanisms.

4.5.2.1 The imaging subsystems should be located no less than 25 feet (7.6 meters) above the roadway, median, or shoulder; depressed medians excepted and as close to the traveled roadway as possible if located over medians or shoulders.

4.5.2.2 The imaging subsystem shall be positioned so that the axis for azimuth rotation is vertical and that the image formed provides a level horizon.

4.5.2.3 The imaging subsystem should be mounted in such a manner that clear views of the upstream and downstream roadway traffic may be obtained.

4.5.2.4 The primary candidate locations for the imaging subsystem are on top of sign bridges or cantilevered signs extending over the roadway or shoulder. Secondary candidate locations are on luminaire poles or the like. Locations subject to vibration should be avoided.

4.5.2.5 The mounting should be such that when the imaging system is depressed, a view of the roadway as close as possible to the vertical to the sensor mount should be obtained.

4.5.2.6 The primary view of the imaging subsystem should be an upstream view with the imaging subsystem located as nearly as possible above the juncture of the shoulder and the rightmost highway (downstream view) traffic lane. Offramps are to be considered as shoulders in this paragraph.

4.5.2.7 The imaging forming and sensing subsystems shall be contained in a weathertight enclosure.

4.5.2.8 The image system enclosure should provide protection to the image forming path to prevent direct exposure to the effects of precipitation.

4.5.2.9 The mechanisms for directing the imaging subsystems in azimuth and elevation should be protected from the effects of weather and impinging water from irrigation sprinklers or other like sources.

4.5.2.10 Weatherproof connectors should be provided on the imaging enclosure and to the directing mechanism for interconnecting cables.

4.5.3 Electronic Subsystems

The electronic subsystems are all subsystems with power, data, communication, and like functions not wholly a part of the directing mechanism or image forming and sensing.

4.5.3.1 The electronic subsystems should be housed in a NEMA approved enclosure which is weatherproof and sealed against the direct entry of impinging or engulfing water.

4.5.3.2 The electronic subsystem housing should be accessible for routine maintenance and inspection and should pose no occupational or safety hazard to personnel performing such tasks on account of placement or positioning.

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4.5.3.3 The electronic subsystem housing should utilize weathertight connections for electrical power and signal wires and/or cables.

4.5.4 Cabling

4.5.4.1 The cabling between the imaging subsystems enclosure and the electronics subsystems enclosure should be weatherproof and equipped with compatible weatherproof connectors.

4.5.4.2 The cabling should be protected from physical damage by protective placement or enclosure in conduit.

4.5.4.3 A single cable with single connector at each end is desirable.

5.0 PERFORMANCE REQUIREMENTS

5.1 Traffic Parameters

The WADS shall provide performance in the determination of traffic parameters in the Test Section as delineated in Table I.

Table I

Lanes surveyed*	2 or more
Direction*	Downstream
Test section length*	Minimum of 200 ft (61 m)
Parameters	
Lane count	Up to 3000 veh/hr/lane
Lane occupancy	0 to 50%
Lane speed (space mean)	0 to 80 mph (0 to 129 kph) averaged over a selected time interval
Density (concentration per lane in the Test Section)	0 to 150 veh/mi (0 to 93 veh/km)

*For parameter measurements

Note: The accuracy of any measurement shall be no worse than 3% of the full scale of the measurement.

5.2 Imaging

The WADS shall provide the performance in providing views of highway as delineated in Table II.

Table II

Field of view	~9°H x ~7°V to at least ~50°H x ~38°V
Aspect ratio	4:3 hor. to vert.
Maximum distance	1320 feet (402 meters)
Minimum distance	20 feet (6.1 meters)
Azimuth direction	±360°
Tilt	+5° to -45°
Vertical resolution	0.015°
Horizontal resolution	0.030°

6.0 PHYSICAL CHARACTERISTICS

6.1 General

It is intended that the imaging portion of the WADS have such physical characteristics that it may be put in the installed position or removed from there by one person. Similarly, the imaging portion should not place undue strain on the structure to which it is affixed. The electronics portion will probably be semipermanently mounted in an approved enclosure. The separate subsystem should be independently removable for servicing.

6.2 Weight

6.2.1 The imaging portion weight shall be less than 33 pounds (15 kilograms).

6.2.2 The electronics portion weight excluding enclosure shall be less than 66 pounds (30 kilograms).

6.3 Volume

6.3.1 The imaging portion shall be contained within an envelope of dimensions not to exceed 18 x 6 x 6 inches (46 x 15 x 15 cm).

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6.3.2 The electronics portion is to be housed in an enclosure no larger than 22 x 24 x 9 inches (56 x 61 x 23 cm).

6.4 Mounting

6.4.1 The mounting for the imaging portion shall be adaptable to flat and angular surfaces as well as the tubular sections of luminaire mast arms.

6.4.2 The electronics enclosure shall be vertical pole or vertical surface mounted.

6.5 Power Service

All designed functions shall be performed when the voltage, frequency, interruptions, and transients are within prescribed limits.

6.5.1 Voltage

The voltage range shall be 95 to 135 volts alternating current. The nominal voltage shall be 117 volts.

6.5.2 Frequency Range

The operating frequency range shall be 57 to 63 hertz.

6.5.3 Interruptions

Power interruption pairs greater than 1.5 seconds apart shall be treated as separate occurrences.

6.5.3.1 Power interruptions of 0.5 second or less shall have no effect on the functional performance of the WADS as a whole or any subsystem.

6.5.3.2 Power interruptions greater than 0.5 but less than 1 second shall be ignored or cause a reversion to a start-up condition when power is restored.

6.5.3.3 Power interruptions longer than 1 second shall cause a reversion to a start-up condition when power is restored.

6.5.4 Transients

The WADS as a whole and all subsystems shall maintain all designated functions when the pulse levels of 6.5.4.1 and 6.5.4.2 occur independently on the service power lines.

6.5.4.1 High Repetition Pulse Transients

The test pulses shall not exceed the following conditions:

1. Amplitude - 300 volts both positive and negative
2. Peak Power - 2500 watts

3. Repetition - one pulse every 1/30th of a second moving uniformly over the full wave of the line frequency sweeping across 360 degrees every 3 seconds

4. Pulse Rise Time - 1 microsecond

5. Pulse Width - 10 microseconds

6.5.4.2 Low Repetition Pulse Transients

The test pulses shall not exceed the following conditions:

1. Amplitude - 600 volts ±5%, both positive and negative polarity

2. Energy Source - 10 microfarad ±10% capacitor, oil filled, noninductive, internal surge resistance less than 1 ohm

3. Repetition - 1 discharge every 10 seconds

4. Pulse Position - Random across the 360 degrees of the line cycle

6.6 Environmental

The temperature and humidity limits prescribed are those within the equipment enclosures. Vibration and shocks are applied to the enclosures.

6.6.1 Temperature

The operating ambient temperature range shall be from -30°F (-34°C) to +165°F (+74°C). The storage temperature range shall be from -50°F (-45°C) to +200°F (+93°C). The rate of change of ambient temperature shall not exceed 30°F (17°C) per hour, during testing, and the relative humidity shall not be allowed to exceed 95 percent.

6.6.2 Humidity

The relative humidity shall not exceed 95 percent over the temperature range +40°F (+4.4°C) to +110°F (+43°C).

6.6.3 Vibration

The WADS shall maintain all prescribed functions and physical integrity when subjected to a vibration frequency of 5 to 30 cycles per second with an amplitude of 0.5 gravity (peak) applied to each of three mutually perpendicular planes.

6.6.4 Shock

The major units of the WADS shall suffer neither permanent mechanical deformation nor any damage that renders the unit inoperable when subjected to a shock of 10 gravities applied in each of three mutually perpendicular planes. Shocks will be applied by drop tests of the WADS imaging or electronics enclosures.

6.7 Design and Construction

The WADS units shall be modular in design. Circuit boards shall be readily accessible for maintenance utilizing either extender boards or cables.

6.7.1 The design and construction shall emphasize ease of maintenance while preserving structural integrity.

6.7.2 The design and construction shall avoid thermal hot spots by allowing free circulation. Forced ventilation shall be avoided.

6.7.3 The design should avoid the necessity for specialized test equipment insofar as possible. Ordinary electronics test equipment should suffice for maintenance and repair procedures.

7.0 SAFETY CONSIDERATIONS

7.1 High Voltage

While the WADS imaging system is operating, voltages in excess of 1 kilovolt are present. Extreme caution must be observed by personnel if it becomes necessary to operate the WADS with the protective covers removed.

7.2 Optical Surfaces

Proper operation of the WADS requires that the optical and image forming elements remain free of contamination. Cleaning and adjustments must only be performed by authorized personnel in accordance with established procedures.

7.3 Operational

The imaging sensor may be irreparably damaged if pointed at the sun. A mechanical shutter or a means to restrict the pointing of the imaging system shall be provided to protect the sensor.

8.0 CERTIFICATION

8.1 Selected WADS units will be required to be certified in accordance with the test procedures outlined in Part 2 of NEMA Standards Publication No. TS 1-1976, "Traffic Control Systems."

8.2 All WADS units will be tested to perform all designated functions over the service voltage range.

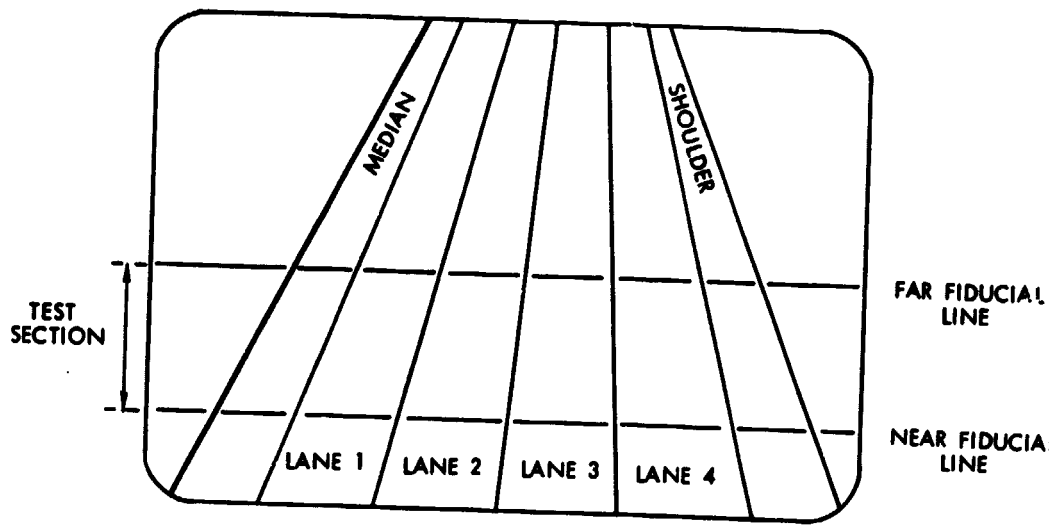

Figure 1. Highway Image

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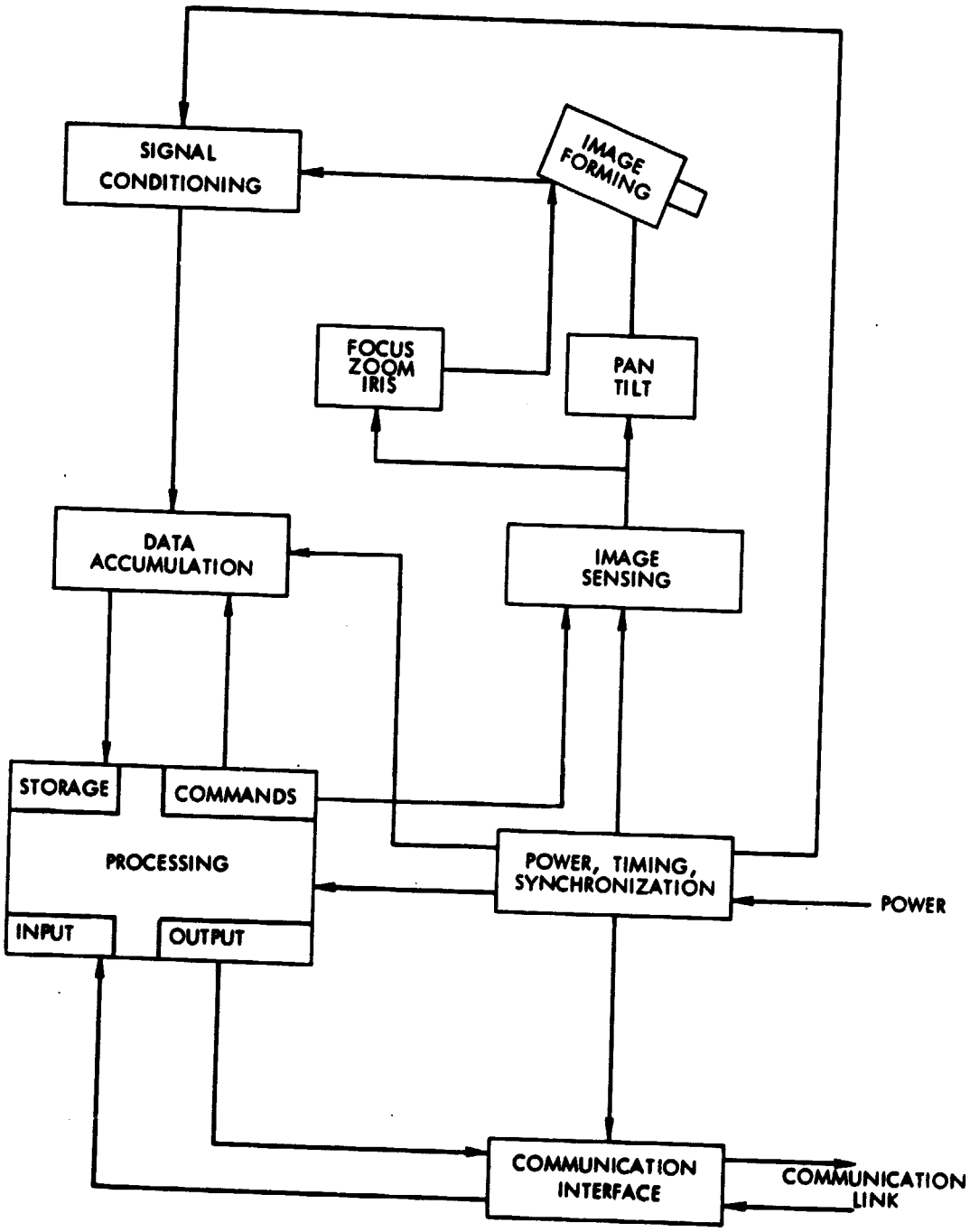

Figure 2. WADS Functional Block Diagram