# AUTOMATIC VEHICLE )NITORING SYSTEMS STUDY Report of Phase 0 

# Vol. 2. Problem Definition and Derivation of AVM System Selection Techniques 



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## PREFACE

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## FOREWORD

This report was prepared for distribution to public safety planners for the purpose of providing them with a compact source of information regarding improvements in efficiency and cost benefits obtainable with varıous classes of operational and proposed automatic vehicle monitoring (AVM) systems. An AVM system can contribute to emergency patrol effectiveness by reducing response times and by enhancing officer safety as well as by providing essential adminıstrative control and public relations information. This complete report and the Executive Summary (Vol. 1) were prepared by the Jet Propulsion Laboratory of the Calıfornia Institute of Technology using the results of studies sponsored by the National Science Foundation.

Special computer programs are described which can simulate and synthesize AVM systems tailored to the needs of small, medium and large urban areas. These analyses can be applied by state and local law enforcement agencies and by emergency vehicle operators to help decide on what degree and type of automation wall best suit their individual performance requirements and also the possible reduction in the number of vehicles needed which could substantially reduce operating expenses.

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#### Abstract

A set of planning guidelines is presented to help law enforcement agencies and vehicle fleet operators decide which automatic vehicle monitoring (AVM) system could best meet their performance requirements. Improvements in emergency response times and resultant cost benefits obtanable with various operational and planned AVM systems may be synthesized and simulated by means of special computer programs for model city parameters applicable to small, medium and large urban areas. Design characteristics of various AVM systems and the implementation requirements are illustrated and costed for the vehicles, the fixed sites and the base equipments. Vehicle location accuracies for different RF links and polling intervals are analyzed. Actual appli- catıons and coverage data are tabulated for seven cities whose police departments actively cooperated in the JPL study. Volume lof this Report is the Executive Summary. Volume 2 contains the results of systems analyses.


G. R. Hansen

# AUTOMATIC VEHICLE MONITORING SYSTEMS STUDY 

## EXECUTIVE SUMMARY

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# AUTOMATIC VEHICLE MONITORING SYSTEMS 

George R. Hansen

## I. INTRODUCTION

In this report, the results of the first phase of a three-phase program to aggregate existing information on Automatic Vehicle Monitoring (AVM) Systems are presented in terms of performance, urban characteristics, operating modes, and cost in a way that will assist prospective AVM User Agencies to make valid comparisons and selections from among the many competing AVM techniques and AVM Systems. This phase (Phase 0) of the study was performed by the Jet Propulstion Laboratory (JPL) for the National Science Foundation (NSF). As orıginally concelved by NSF and JPL, the AVM Systems study program would include the following three phases.

Phase 0 $\quad$| Problem Definition and Derivation of AVM System Selection |
| :--- |
| Techniques (in this Report) |

Phase I $\quad$| Critıcal Research and Verıfication of the Efficacy of AVM |
| :--- |
| System Selection Techniques Through Computerized System |

Phase II | Simulation. |
| :--- |
| Proof of Concept Experiment Demonstrating the Efficacy of |
| Selected AVM Systems in Urban Environments. |

In brief, the Phase 0 research was concentrated in three areas: (1) Compilation of a broad information base on AVM technology and urban characterıstics, (2) adaptation of computerızed analytical techniques needed in the AVM System selection process and in cost benefit trade-offs, and (3) application of AVM System selection process by manual iteration to small, medium and large model cities.

Frequent reference is made in this Report to "AVM techniques" and "AVM Systems". The term "AVM technique" is used to denote the technology required to acquire a fix on a vehicle, while "AVM System" is used to denote the integration of all functional elements required to locate and keep track of vehicles in some automated fashion.

## II. SUMMARY OF AVM SYSTEMS STUDY RESULTS

## A. WORK ACCOMPLISHED IN PHASE 0

A broad range of information concerning automatic vehicle monatoring (AVM) was compiled from the existing literature, including: (1) Varıous vehicle location sensing techniques, (2) all functional elements of the total AVM system, and (3) various sized cities with representative geography, topology, demography and urbanology. The information obtaned from the literature was supplemented by data obtained directly from police department representatives of seven Southern California cities that partıcipated in the User Group Advisory Committee (UGAC).

Several computerized analytical techniques were developed. City models representative of those characteristics that affect AVM selection were developed for use in the general cost benefit solutions. An analytical technique for predicting vehicle polling rates achievable for the various location sensing techniques in a full AVM system configuration was also developed. Algorithms were developed to estimate the accuracies achievable by a large variety of AVM systems using the probabalistic distributions for three independent variables: (1) vehicle speed, (2) inherent accuracies of location sensing techniques, and (3) vehicle polling intervals.

Preliminary analyses were performed to determine first-order cost estimates for AVM Systems as a function of the various vehicle location sensing techniques when used in small, medium and large cities. Prelıminary analyses of the accuracies achievable with various AVM systems were also performed. Various AVM system configuration options were developed, and promising options were examıned for possible cost benefits to seven UGAC cities.

## B. PRELIMINARY CONCLUSIONS

1. AVM Class should indicate effects on urban environment. From the viewpoint of the prospective AVM system user, the traditional classifications of vehicle locating systems (1.e., piloting, deadreckonıng, triangulation, trılateration, and proximity) do not necessarlly reflect the impact of an AVM installation on the local urban scene. It is believed that the prospective user's needs would be better met if vehicle montoring classifications were based on system element types and functions as follows:

| Class 0 | Manual Monitoring. No AVM |
| :--- | :--- |
| Class I | AVM. No modifıcation to the urban environment. <br> (exısting RF links) |
| Class II | AVM. Autonomous signposts throughout urban area |
| Class III | AVM. Sparsely distributed special RF sites |
| Class IV | AVM. Monitored signposts throughout urban area |

2. AVM cost benefits obtainable by medium and large cities. The preliminary cost analysis indicates that the cost benefit break-even point occurs for a medium sized city with an area of about $100 \mathrm{~km}^{2}\left(40 \mathrm{ml}^{2}\right)$ and with roughly 50 vehicles. In other words, cities larger in size could expect a positive and increasing benefit with size, up to a certain point. Conversely, cities below this medium size probably would not realize any cost benefit. This conclusion was based on 5-year estimates of AVM system costs and savings.
3. No cost benefits derived from monitored signpost systems. None of the Class IV systems produced a cost benefit for the cities studied, generally because the rental rates on telephone lines raise the equipment costs excessively.
4. AVM System accuracies greater than technique accuracies. In general, the $95 \%$ total system accuracy can be expected to be significantly greater than the inherent accuracy of the location sensing technique. Usually the system accuracy is no less than three times the inherent technique accuracy.
5. Vehicle polling intervals determine AVM system accuracies. It appears that the polling interval will dominate system accuracy and that the polling interval can only be shortened at the expense of RF resources dedicated... to AVM purposes. Because of the present and predicted future demand on RF resources, this is one area that demands optimization.
6. Critical research required for verification of selection technıque. The results of the first phase of the AVM study effort should be used with caution and should not be construed as specific recommendations at this point. The second phase of the analytical work should be completed to verıfy the results of the first phase.

## C. PROGRAM RECOMMENDATIONS

1. It is recommended that the second phase (Phase I) of the AVM Systems study proceed.
2. It is further recommended that mission agencies such as the Law Enforcement Assistance Administration (LEAA) and/or the Department of Transportation (DOT) sponsor the Proof of Concept Experiment, or third phase. The tests presently planned jointly by the city of Los Angeles and DOT could effectively serve this purpose. This could be accomplished by closely coordinating the analytical techniques developed in this study with the Los Angeles Police Department, the Southern Calıfornia Rapid Transit District, LEAA and DOT and making the analytical tools available to the city for use in the design of the experiment.

## III. CLASSES OF AVM SYSTEMS

## A. CLASSIFICATION RATIONALE

Traditionally, AVM systems have been classifaed in the 1iterature according to the method used to locate the vehicle within an urban area. Recognizing that all AVM systems have certain elements in common and that some systems have unique elements, an alternate classification scheme was developed for the purpose of this study. This classification not only implies the type of AVM system but also suggests the physical impact that the system elements and functions will have on the local urban environment. The following groupings of system elements suggested the classification scheme:

## Functional Elements Common to All AVM Systems

(1) Existing communications system.
(2) Vehicle polling subsystem.
(3) Landline data links.
(4) Telemetry data/polling handler.
(5) Telemetry link (common to most).
(6) In-vehıcle equiprnent, such as data processor, telemetry data encoder, polling processor, and signpost sensor
(7) Vehicle location computer.
(8.) Information display subsystem.

Functional Elements Unique to Specific AVM Systems
(9) Autonomous signposts; signpost sensor in vehicle (Class II).
(10) Fixed synchronızed RF transmitter sites (Class III).
(II) Monitored signposts, vehicle sensor on signpost (Class IV).

A discussion of each of these AVM functional elements follows:

1. Existing communications system. As a practical consıderation, AVM s.ystems will probably be integrated with the existing voice communication and vehicle polling RF links, especially for the telemetered location data between " the vehicle and the dispatch center.
2. Vehicle polling subsystem. This interrogation device or procedure enables the vehicle location computer (VLC), described in Element 7, to know which vehicle corresponds to which set of location data. Polling may be either an operating procedure or an active element that allows the dispatcher to obtain locations of specific vehicles.
3. Landline data link. This data link is a landline supplyang data to the VLC (Element 7). It may either be relatively short, leading from the telemetry data/polling handler (Element 4) to the VLC, or it may be quite extensive, collecting data from monitored signposts throughout the covered urban area, or it may be somewhere in between these in its extent, bringing data from a relatively small number of fixed $R F$ sites.
4. Telemetry data/polling handler. This device is included because AVM systems deal with data that are different (e.g., digital) in character from that used by the dispatcher in voice communncation with the vehicles. Furthermore, if the vehicle polling subsystem (Element 2) provides for selective polling, then there are likely to be corresponding additional requirements on the communncation system.
5. Telemetry link. Since it is tacitly assumed that the AVM system will not restrict the mobility of the fleet vehicles, some kind of communication-at-a-distance is essential. In some systems, the telemetry link is assumed to share or be in addition to the RF link now used for volce communications. In other systems the telemetry path might be between the vehicles and sparsely distributed synchronized RF sites. In still other AVM systems, the telemetry path may be relatively short, being only from the vehicles to signposts distributed throughout the urban area. In that case, the transmission medium could conceivably be sonic, optical, or even magnetic, instead of radio.
6. In-vehicle equipment. Depending on the AVM system, some or all of the four following devices may be carried in the vehicle.
a. Vehicle data processor. This device recelves raw vehicle location data either from the officer or from signpost sensors. It does whatever data processing is done on-board, then adds the vehicle identification data, and passes this information along to the telemetry data encoder, described next.
b. Vehicle telemetry data encoder. This device puts the vehicle location data supplied by the vehicle data processor into the telemetry link (Element 5).
c. Vehicle polling processor. This device enables the vehicle to respond properly when polled, and may range in complexity from a clock to an RF signal decoder.
d. Signpost sensor. Where the densely distributed autonomous signpost concept is used (Class II), the signpost sensor must be carried in the vehicle. This sensor is required to read the signpost ID/location. Location data may be acquired by coded optical, infrared, sonic, or magnetic means besides radio.
7. Vehicle location computer (VLC). This device transforms the vehicle location data into location points or coordinates for use by the information display subsystem (Element 8). It also informs the display subsystem as to the identity of the vehicle to which the location data belongs. The VLC may also interface with the Computer-Aided Dispatch System.
8. Information display subsystem. This device indicates to the dispatcher where the vehicles are currently located (or were when last polled). It may also identify the vehrcle's status. As in the case of manual aids used for vehicle location in Class 0 , the possible range of complexity and sophistication may range from a simple printer to an elaborate electro-optical device supported by a computer. It should be noted that the display subsystem is virtually independent of the location technique used.
9. Autonomous signposts used in Class II AVM. Each autonomous wayside or buried signpost has a location ID and must be recognizable and readable by the signpost sensor in the vehicle. The signpost telemetry link to the vehıcle may be by radio, pulsed light, infrared, sonıc, or magnetic means.
10. Fixed synchronized RF transmitter sites used in Class III AVM. These RF sites are a relatively small number of special-purpose transmitters which broadcast synchronized signals that can be used to determme the locations of receivers on vehicles by means of navigation techniques. The characteristics of these signals could be FM phase, pulse, or noise correlation. Some of these sites may also recelve retransmitted signals from the monitored vehicles.
11. Monitored signposts used in Class IV AVM. Each monitored wayside or buried signpost requires a vehicle sensor that will transmit the vehicle's ID data received and also identify 1 ts own location to the central collection station. These signposts may sense vehicle motion, or they may detect pulsed Light, infrared, or ultrasonic signals or receive RF signals through buried antennas.

## B. AVM CLASS DESCRIPTIONS

The vehacle location system classes, based on their physical impact on the urban environment, are shown in the following list and are described in greater detail in subsequent paragraphs and accompanying figures. For reference, the traditional vehicle location classifications are noted as indentures.
(1) Class 0 Manual Monitoring. No AVM
(a) Piloting
(2) Class I AVM. No Modification to Urban Environment (Existing RF Links)
(a) Officer Update
(b) Dead Reckoning
(c) Navigation (Using Existing RF Beacons)
(3) Class II AVM. Autonomous Signposts Throughout Urban Area
(4) Class III AVM. Sparsely Distributed Special RF Sites
(a) Triangulation
(b) Trilateration
(5) Class IV AVM. Monitored Signposts Throughout Urban Area
(a) Vehicle Proximity

1. Class 0 Manual Monitorıng; No AVM. Thıs baseline (piloting) class is included in the listing of vehicle location techniques purely for comparative purposes. In Class 0, the location monitoring methods (Figure l) range from those relying solely on the dispatcher's memory, through manually updated mechanical and visual aids, to keyboard-updated computer displays which keep current each vehicle's location and status based on verbal or digital communications between dispatcher and vehicle.
2. Class I AVM with no modifications to urban environment. All AVM systems require the installation of certain equipment in the command center to accomplish the automation of vehicle monitoring. All AVM systems also require the installation of some device in or on the monitored vehicles. But systems in Class I require nothing further, though they perforce utilize RF resources.


Figure 1. Class 0 Manual Monıtorıng, No AVM

A typical Class I AVM configuration is shown in Figure 2. Each AVM command center must contain a display subsystem, a vehicle location computer, a vehicle polling subsystem, and a telemetry data/polling handler, which are described in Section IV. Each vehıcle requires location sensors, a data processor, a telemetry data encoder, and a polling processor. Class I AVM systems are based upon a variety of location technıques and algorithms which include the following: (a) Officer update techniques, in which the functions of the vehicle's sensors and its data processor are performed by an occupant of the vehicle. (b) Deadreckoning systems are included if the requisite updating does not require the installation of fixed location reference equipment in the environment. (c) If the AVM systems use existing navigation beacons or AM broadcasting stations, they are also included in Class I because the required stations are assumed to be part of the urban environment.
3. Class II AVM with autonomous signposts throughout urban areas. The defining characteristic of Class II AVM systems is the installation of autonomous signposts in strategic wayside or buried locations at intersections throughout the covered urban area. These location reference sites are autonomous in that they communicate their identity only to the vehicles and not to the command center.


Figure 2. Class I AVM; No Modifications to Urban Physical Environment

The location information provided by the signposts to the vehicle may be either an identification code or the geographic coordinates of the location. Since the vehicle location accuracy provided by systems in Class II is dependent upon signpost spacing, greater accuracy can be achneved in critical areas by locally increasing the signpost density to one per intersection or per lane. A typical Class II system configuration is shown in Figure 3. Signpost systems can be "pure", in that all location information is derived from the fact that a monitored vehicle is (or was) near a signpost; or they can be "hybridized", with the fact of signpost proximity used either to augment, calıbrate, or reinitialize the determination of vehicle locations obtained by other means, such as odometers. If a hybrid system does not require a data link in the environment, it is placed in Class II. If the hybrid system requires a data link from the signposts but no special-purpose fixed RF sites, it belongs in Class IV. If it has both a data link in the field and special-purpose fixed sites, it is in Class III.
4. Class III AVM with sparsely distributed special RF sites. Thıs AVM class includes those systems that require the installation of a relatively small number of special purpose fixed RF sites, where a "fixed site" either broadcasts or recelves over a relatively large urban area with a radius of 5 to 11 km ( 3 to 7 miles).


Figure 3. Class II AVM, Autonomous Signposts Throughout Urban Area

Data links in the environment are required to maintain synchronization for triangulation or trilateration purposes. Since the number of fixed sites is relatıvely small, these data synchronızation links could be microwave rather than landíine. Figure 4 shows a typıcal Class III configuration. It is optional only in Class III systems whether the telemetry link from the vehicle be along the existing communication system or through the-special-purpose RF sites. In either case, RF resources are utilized for that link.
5. Class IV AVM with monitored signposts throughout urban area. Systems in this class contain monitored signposts installed in strategic waysade or buried locations throughout the covered urban area for the purpose of sensing the proximity and identity of signals transmitted from vehicles. A Class IV data lank does not share the use of RF resources with the existing communication system but uses telephone lines, which may make this class of AVM systems very attractive for some applications. A typical Class IV system configuration is shown in Figure 5.


Figure 4. Class III AVM; Sparsely Distributed Special RF Sites


Figure 5. Class IV AVM, Monitored Signposts Throughout Urban Area

## IV. VEHICLE LOCATION TECHNOLOGIES AND COSTS

## A. PROVED AVM TECHNIQUES

This section contans a narrative description and a complation of the cost and performance parameters of operational or proved techniques used for automatic vehicle monitoring (AVM). Schemes primarily intended for vehicle identification, such as those used in rail freight or extensions of point-of-sale methods are not included. In this report, the vehicle monitoring techniques are categorized into five broad classes, based on system element types and functions: Class 0, Manual Monitoring, no augmentation of location information; Class I AVM, no additions to the urban environment; Class II AVM, densely distributed autonomous signposts; Class III AVM, sparsely distributed special transmıtting/receiving fixed RF sites; and Class IV AVM, densely distributed monitored signposts. In Table l, the proved vehicle location methods are listed by AVM Class along with estimated costs (as of 1974) for unique system-required equipments installed in each vehicle and at each signpost or special fixed site.

1. Functional diagram correlating various AVM techniques. In order to make equipment and cost comparisons, a functional block diagram combining the elements that make up all of the AVM techniques was generated. This block diagram (Figure 6) demonstrates the equipment and functional commonalaty among the various techniques. In most techniques, the functional elements can also be physically identical, such as the location/vehycle ID/status register. Variations in costing such elements are due to other factors, such as achievable location precision, fleet size, and amount of status telemetry desired which all affect register length but are technique independent.

Figure 6 illustrates the numerous optional methods available for performing the vehicle location function which make AVM system comparisons difficult. For example, the various Class I techniques can either process the location data on the vehicle or transmit the raw data to the base station. In the Class III techniques, the vehicles may be polled either through the normal 2 -way radio or through a special telemetry link used for vehicle location purposes.

Table 1. AVM Classes, Systems and Costs of Functional Elements Installed

| AVM Class and System | Element Costs, \$ |  | AVM Class and System | Element Costs, \$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | Vehicle | Fixed Site |  | Vehicle | Fixed Site |
| $\begin{array}{ll}\text { Class 0. Manual Monitoring No Augmentation of } \\ & \text { Vehicle Location Information }\end{array}$ |  |  | Class II Autonomous Signposts Throughout Urban Area |  |  |
| Class I. No Modifications to Urban Environment (Existing RF Links) |  |  | (1) Active signposts <br> (a) Radıo beacons <br> Low frequency <br> Citizen band, VHF <br> X -band beacon <br> (b) Ultrasomic signposts <br> (c) Optical, infrared <br> (d) Buried antennas <br> (2) Passive signposts <br> (a) Buried Magnets <br> (b) Reflective patterns <br> Coded on signposts <br> Coded on roadway <br> (c) Bursed resonant loops | $\square$ |  |
| (1) Officer update systems <br> (a) Keyboard entry <br> (b) Stylus map <br> (2) Dead reckoning systems <br> (a) Two accelerometers <br> (b) Two velocimeters Laser, orthogonal Laser/compass Ultrasonic | $\begin{array}{r} \square \\ 120 \\ 2535 \\ \hline \\ 500 \\ 715 \\ 805 \\ 485 \end{array}$ | $\square$ <br> 0 <br> 0 |  | $\begin{aligned} & 145 \\ & 145 \\ & 160 \\ & 170 \\ & 170 \\ & 135 \\ & \hline 95 \\ & \hline 580 \\ & \hline 135 \\ & 135 \end{aligned}$ | 165 <br> 145 <br> 275 <br> 160 <br> 155 <br> 120 <br> 110 <br> 10 <br> 85 <br> 125 <br> 95 |
| (c) Odometer/compass | $\longrightarrow$ | $\underline{\square}$ | Class III. Sparsely Distributed Specıal RF Sites |  |  |
| Magnetzc compass <br> Gyro compass <br> (3) Navıgatıon, exısting beaçons <br> (a) OMEGA systems <br> Differential <br> Relay OMEGA <br> (b) LORAN (A, C, or D) | 285 <br> - <br> - <br> - <br> - <br> 4580 | 0 <br> 0 | (1) Trilateration systems <br> (a) Phase TOA <br> Narrow-band <br> Wide-band <br> (b) Pulse TOA <br> (c) Interferometer, noise <br> (2) Triangulation systems <br> (a) Rotatıng beams (HONORÉ) <br> (b) Direction finding | $\begin{array}{r} \square \\ 100 \\ 2,965 \\ 1,435 \\ 885 \\ \square \\ \hline \end{array}$ | $\begin{array}{r} \bar{L} \\ 5,000 \\ 11,000 \\ 14,500 \\ 9,000 \\ \hline \end{array}$ |
| Differential <br> Relay LORAN | 2680 505 | 0 0 | Class IV Monitored Signposts Throughout Urban Area |  |  |
| (c) DECCA System <br> (d) AM Broadcast stations | 1010 365 | 0 0 | (1) Radio recelvers <br> (a) Wayside <br> (b) Buried antennas <br> (2) Ultrasome receptors <br> (3) Optical, infrared detectors | -2 135 145 185 185 | $\begin{aligned} & 260 \\ & 265 \\ & 280 \\ & 270 \end{aligned}$ |




Eigure 6. AVM Systems Showing Common and Unique Equipments for Vehicles, Signposts, and Base Stations

Class I, II, and III technıques may use any of the various vehicle polling technıques. Polling does not apply to the Class IV monitored signposts. The consideration of which polling method is to be used may depend heavily on whether or not equipments requiring digitial communication have already been installed.
2. Technical and cost parameters. Virtually every technical performance and cost estimate parameter of a particular vehicle location technique is system-dependent. The AVM system accuracy, the numbers of fixed sites, the message lengths, the data rates, the base station computing, the information displays, software, and RF channel requirements are all functions of the particular application. Some functional elements and performance factors can be determined to a limited extent, such as the cost and coverage radius of the various signposts, RF beacons and traffic presence sensors in Classes II, III, and IV; and also the cost and minımum message requirements of the vehicle sensors and data processors in Class I.

In order that cost estimates could be made for the various AVM techniques, extremely simplified block diagrams of the unique functional elements associated primarily with the vehicle location process were developed. That 1s, only the vehicle sensor and AVM fixed sites associated with the particular technique were considered. These cost figures accompany each of the descriptions and considerations of the method in the following section.

## B. AVM COST CONSIDERATIONS

In addition to the costs associated wath the vehicular and fixed site functional elements required for the basic location process, there are the costs of yearly maintenance and vehicular radio additions or modifications for transmitting and receiving AVM signals. Estimates of the vehicular costs (as of 1974) for each class of AVM are presented in Table 2. In this table, the radio cost and the radio modification columns represent optional choices. That is, the radıo modification cost is not applicable where a separate radio for AVM signals is selected.

The costs for fixed sites equipment, unstallation, operational maintenance, data link, and maleage charges per mıle per month are summarized in Table 3 for Classes II, III, and IV.

Table 2．Vehicle Equipment Costs＊for All AVM Classes and Systems

| IEHLOST $\quad$ HUL LOSTS PEF MEHILLE IH A |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  |
| CLASS I <br> TEGHHIDIUE | SEHSOF | FFOL | FHIID | FFII．VIOII | Int | ［1］ |
| －E＇ISOHPI | $\div$ | 4 | 1506 | 50.1 | 3 | 15 |
| STiLuS the | 24E5 | 35 | 1269 | 59 | 5 | － |
| E－HCEELEFOHETEF： | 4619 | 100015 | 1209 | 209 | 1619 | 100 |
| LFSEP IELUIITMTF | 504 | 1090 | 1ごす | 360 | 135 | 15 |
| ULTFFGOHIE MELO | $2-6$ | 6819 | 1290 | 206 | 160 | 150 |
| EOFPHSS OIDTETEF | 265 | 1695 | 1209 | 20in | 20 | ＋ 4 |
| COTFHSS LFSEF HEL | －5 | 1000 | 1209 | E09 | 15 | 45 |
| CHFSS U－SOHIIS IEL | 38 |  | 1295 | 200 | 100 | 96 |
| DHEGA | 2596 | $\square$ | 1296 | 260 | 16 | $\cdots$ |
| LIFPH | 2569 | $\underline{\square}$ | 1 Cb | 290 | Es | $\bigcirc$ |
| TELCA | Sticter | －1 | 1204 | 2 | 5 | $\checkmark$ |
| AITSTATIOH， IIFF．OHEEA | 200 | 0 | 1209 | 20.0 | T610 | 6.9 |
| IITFF：LOFHe | E6H | 8 | 12010 | －101 | 30 | $\rightarrow$ |
| DIFF＝FH1－STH． | 315 | 4 | 1 EG日 | 150 | 510 | 80 |
| FELA＇ | 3 | 0 | 1209 | 130 | 0 | 1019 |
| FELA＇i LOPHI CLFSS II | －50 | $\square$ | 12000 | 156 | 6. | 106 |
| EUFIEI FĖ＝LOUF： | 96 | $\underline{0}$ | 1 ごず9 | 50 | 「「 | 15 |
| FEFLEETIHG SIGHE | 459 | $\underline{\square}$ | 12061 | 5 | 130 | 2 |
| FEFLEETIHG FIGHI | $\checkmark 5$ | $\square$ | 1296 |  | 83 | 15 |
| ：－EAtIIFOST | 15 | 9 | 1200 | 519 | T | 16 |
| HF＊ LF FOET HOST | 105 | 9 | 1200 | 5 | － | 10 |
| LF FOST | 109 | 0 | 1265 | 59 | $\pm$ | － |
| EUFIET ATGHETS | 54 | $\square$ | 12g | 519 | － | S |
| ULTFHEOHIE FOET | 85 | 5 | ． 106 | 56 | 59 | － |
| TFFFFIE SEISOF | 9 | E | 1 O60 | 59 | 4 | 10 |
| CLASE III | 6 E | $\square$ | 12090 | 165 | －71 | 5 |
| HIT－EAHII FIT FHFEE | 295 | 1 | 15 | 36 | 909 | 20 |
| FULSE T－DTAFFIUFL | 25 | 9 | 8 | $\xrightarrow[9]{9}$ | 15.5 | 25 |
| HIISE COFPELATIOH DIFECTIOH FIHIEF | 785 | 9 | $\square$ | 0 | 1610 | 2 |
| IIFEETIOH FIHIEF <br> CLRES III | 35 | $\square$ | $\square$ | 0 | 15 | － |
| TRAFFIE LODFS | 85 | $\underline{\square}$ | $\square$ | $\square$ | 8 | 16 |
| HF＇＇SIDE FATIS | 7 | 0 | 9 | 0 | 4 | 16 |
| PHOTO I－F FETELT | 115 | 9 | $\square$ | 9 | － | 15 |
| ULTFHEOHIIC IETECT | $1 \Sigma^{5}$ | 9 | $\underline{\square}$ | 6 | ES | 15 |

[^0]Table 3. Fixed Site Costs* for Class II, III, and IV AVM Systems

FI: ENOST

TELHIIGUE EOUIF LLHSEI
t E'BOAFII
5

E-ACEELEFOHETEF:
LASEF IELOLINTF
HLTPFGOHIT HELO
EOHPHSE OTOIETEF
EOHFHS LAEEF MEL
CIFES :1-EOHIL MEL
DEGA
LUFFHI
aECE
HI-GTATIOHE
IIF $\bar{T}=$ OIELA
IITF: LOPFH
ITFF: AITETA.
FELF:
FELAH LOFHH
CLASE II
SUFIEI FES. LOOFS
FEFLECTITIG SIGIS
FEFLECTITG FOHZ
$\because$ :-Fin POST
$\mathrm{HF}=1 \mathrm{HF}$ FOST
LS FGST
ZUPIET HACHETS
ULPHEOHIC FOST
TFAFFIG EEHSOF
CLRSS III

| HAFP-EHITI FH1 FHASE | 45610 | 56 | 5150 | 2 | 5 |
| :---: | :---: | :---: | :---: | :---: | :---: |
| HIJ-EAl产 Fil FHFSE | -9519 | 1565 | 5519 | $20^{56}$ | $\underline{0}$ |
| PILSE T-i-FFFFIMAL | 12069 | 25090 | 560 | 20196 | $\square$ |
| HOISE EOFFELHTIOH | $\bigcirc 506$ | 15901 | 500 | 2610 | $\square$ |
| SIFELTIOH FITIEF | 260169 | 15619 | 129 | 25 | 5 |
| CLFSS IU |  |  |  |  |  |
| TFFFFIC LOUF'S | 165 | 113 | 16 | 13 | 4 |
| HFiSIDE FHIIS | 160 | 113 | 25 | 13 | 4 |
| FHOTG I F IETECT | 179 | 113 | 2 | 13 | $\stackrel{\square}{4}$ |
| ILLTFHSOHIC DETECT | 16E | 113 | 25 | 13 | 4 |

[^1]Additional costs associated with each AVM technıque when configured as a system are the base station costs and the vehicle polling system costs, given in Table 4. The base station 1 s assumed to include the vehicle location computer, the peripherals, the dispatcher displays, software, and yearly operational maintenance.

1. Vehicle cost parameters. Vehicle costing for an AVM system is a straightforward multiplicative process of determining the total cost to equip all vehicles in the fleet with the appropriate AVM sensor, data processor, vehicle polling equipment, and radıo modification; motorcycles are not considered. If a separate radio link is deemed necessary for AVM purposes, then this additional cost must be added.

If the vehicle fleet has already been equipped with digital message entry devices (DiMED), keyboards, hard-copy printers, gas-plasma or cathode-ray displays, then some of the functional elements required for an AVM system have been established. Prior installation of digital message equipment was not considered in the costing of vehicular equipment.
2. Fixed site costs. Site costs unique to AVM systems are consıdered only in Classes II, III and IV. In determining the system costs, the number of installed units must first be determined. The design algorithms for fixed sites are dependent on the density distributions of intersections, road segments, and lanes, and on the area to be covered.

Most of the Class II AVM techniques that rely on radio ID signals are configured and costed on the basis of one autonomous signpost per intersection. The exception is the HF signpost which is configured on the basis of one unit for each four intersections because of the greater coverage radius. The reflective pattern signs techniques require two installations for each road segment because of the geometry constraints between vehicle and sign, whereas the traffic presence sensors require one installation for each road segment because of the nature of the normal installation. Buried loops and magnets require an installation per lane in each road segment. In addition, each installation is actually a multiple installation; i.e., there must be sufficient loops or magnets to provide adequate coding for each road segment. The cost estimates for fixed sites were based on an average of 2.4 lanes for each road segment, 1.e., about 1 four-lane road for each 6 two-lane roads.

Table 4. Base Station Costs* for All AVM Classes and Systems


[^2]The number of loops at each lane segment was that sufficient to provide a unique base -2 code for each road segment. The number of magnets used is half this value since spaces can be used to provide approximately half the coding bits (magnet for "one", space for "zero").

Since the Class III synchronized RF sites are more sparsely distrıbuted, their numbers are estimated on the basis of urban area for the selected phase and pulse time-of-arrival techniques. The radius of coverage for narrow-band and pulse systems, based on prior tests and experiments, is set at 5 km ( 3 miles). In addition, the requirement that, wherever possible, four or moré antennas should cover the given area is imposed. This procedure provides data for least-squares computation as opposed to the analytic "flat earth " solution of vehicle location. The wide-band antenna coverage radius is set at 11 km ( 7 miles), based on prior tests. Design algorithms were established from the rectangular model cities data as follows:

Number of narrow -band and pulse sites $=6+\frac{\text { area } 1 \mathrm{n} \mathrm{km}^{2}}{10}$
Number of wide-band sites $=4+\frac{\text { area in } \mathrm{km}^{2}}{40}$

The number of fixed sites in the southern California UGAC cities was determined from geometrical gridlined overlays superposed on outline maps of the cities. The outline and site locations for-the cities are depicted in figures that accompany Part 2 of this Report. A minimum number of fixed sites for noise correlation and direction finding was establıshed, recognizing that this number is probably insufficient for all but the smallest cities.

Class IV monitored signposts were configured and costed on the same basis as the equivalent Class II devices. Telephone line rental is, however, included in the site costs where applicable as the line should be considered an equipment cost as opposed to an operation cost.
3. Base station costs. Base station equipment costs were estimated on the basis of both urban area coverage and fleet size. The station's computer costs were estimated on the basis of area, and the software costs were based on fleet size. This separation of cost elements is only partially defensible. It is assumed that a minicomputer is usually used to support the AVM function with varying amounts of bulk storage (disc) to accommodate the city map for output display.

Exceptions are in the Class III time-of-arrival (TOA) methods, where larger machines are assumed. The pulse and noise-correlation techniques also require a larger computer with more speed and versatility than can be provided by a minicomputer because of the inherent capability of servicing many more vehicles per unit time and the need to accommodate a large number of inputs in real time. The software estimate based on fleet size is also difficult to justify totally. Much reliance was placed on prior work estimates and on the judgements of systems analysts.

1 Three estmates each of base station computer and software costs were made based on model city parameters for small, medium and large cities. For the UGAC cities, the costs were determined based on the urban areas and the total fleet size, excluding motorcycles, using linear interpolation.

Display equipment costs are included in the base station costs on the basis of the actual number of dispatchers in the case of UGAC cities. For the model cities, the costs are estimated on the basis of 1 display console for each 50 vehicles or less.
4. Installation costs. Equipment installation costs were obtained by multiplying the cost per unit vehicle and the cost per fixed site installation by the appropriate number of units. Toegether with the base station installation cost, they make up the tabulated total cost. A constant cost value is assumed for the base station, which is a rounded average value of prior estimates made in conjunction with AVM deomonstration tests.
5. Operation and maintenance costs. The estimates of $O-M$ costs for equipment installed in vehicles, at fixed sites, and the base station are based on experience values for both mobile and fixed equupments. In the base station, the principal cost element is for operation and maintenance personnel. Three persons (one per shift) were assumed in all AVM techniques to provide software support or equipment service. Although this assumption may not be justifiable, It was believed that AVM is a comparitively new technology which will probably interface with computer-alded dispatching and digital message systems and that additional service personnel would be required for a substantial time period after the initial installation.

## V. VEHICLE POLLING AND LOCATION PERFORMANCE

Four classes of vehicle polling are considered for AVM Systems:
(1) Synchronous, (2) Commanded or random access, (3) Synchronous with Command capability, and (4) Volunteer or contention. All four techniques are generally applicable to Class I and II AVM Systems.- Synchronous polling and synchronous with command are used mainly in Class III Systems. For the Class IV monitored signpost systems, which use land lines, polling by radio is not applicable in the context used in this description.

All polling techniques are suitable for half-duplex (base station and vehicle on the same frequency), but when the base station relays all vehicle transmissions or when each veh1cle monitors all other vehicles, then the Volunteer technique can only be used on full-duplex (base and vehıcle on different frequencies).

1. Synchronous polling. In this technıque, each vehicIe transmits location data at a preselected time within the fleet polling sequence. Equipment on the vehicle keeps track of the start of the sequence and internally determines when its time to respond occurs. The cost of the vehicle polling equipment installed (as of 1974) is about $\$ 270$.
2. Synchronous with command capability. This polling technique allows the base station to modify the position of each vehicle in the polling sequence. The cost of the vehicle equipment installed is about $\$ 365$.
3. Commanded or random access polling. In this technique, the base station sends a request to each vehicle whenever location data is required. This technique is the most flexible but requires more use of available RF time.
4. Volunteer polling. This contention method requires that each vehicle determine whether the channel is "clear" before transmitting. The cost of vehicle equipment installed is about $\$ 170$ 。

These vehicle polling techniques were evaluated with both a simple one-time radio message transmission and with redundant transmissions where every message is sent twace. The digital message rate is set at 1500 bps . Where equivalent $R F$ channels are assumed, a channel spacing of 25 kHz is used. Message lengths are about 20 bits, or occupy about 15 millisec transmission time. Delays due to equipment turn-on times reduce the achievable polling rate.

# PART ONE: AVM COST BENEFIT INFORMATION BASE 

G.R. Hansen

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## I. PERFORMANCE AND COSTS OF PROVED AVM TECHNIQUES

Costs and performance parameters of 36 operational or proved techniques used for automatic vehicle montoring (AVM) are described and illustrated in this section. Schemes that are primarily antended for vehicle identification, such as those used in rail freight or extensions of point-of-sale methods are not included. In this Report, the vehicle monitoring techniques are categorized into five broad classes, based on system element types and functions: Class 0 Manual Monitoring, with no augmentation of location information; Class I AVM, with no additions to the urban environment, Class II AVM, using densely distributed autonomous signposts, Class III AVM, using sparsely distributed special transmitting/receiving fixed RF sites, and Class IV AVM, using densely distributed monitored signposts. Estimated special equipment and installation costs are as of 1974.

## A. Class 0 Manual Monitoring. No AVM

This is the baseline vehicle location technıque against which other systems should be compared. A manual monitoring system consists of a dispatcher, an existing real-time communication system, and a fleet of vehicles. The dispatcher's knowledge of vehicle locations depends upon voice communications with the officers in the vehicles. Even in the manual vehicle monitoring class, there are several options that affect both performance and costs. The dispatcher can, for example, rely strictly upon his knowledge of each vehicle's designated location or patrol area and its subsequent assignments. Alternatively, he can use some of his RF resources (channels and air time) to interrogate and obtain actual vehicle locations vocally.

A relatively wide range of options is avazlable to the dispatcher for use with Class O nonautomated vehicle monitoring. The simplest visual location aid is just a map on which the assigned beat areas are permanently marked, the dispatcher relying on his memory to locate the vehicles on the map. Numbered magnets or lights may be used which may be updated manually to augment his memory. Elaborate electrooptical display devices are available, which indicate each vehicle's last known location, status, and anticipated destination, all driven by manual input.

The dollar cost of a purely manual vehicle management system is almost bound to be competitive, but the use of RF resources could be prohibitive, and the attainable dispatching performance is also an open question. With an AVM system, the closest avanlable vehicle can quickly be dispatched in response to a service request. Analyses indicate that response times are reduced and fleet efficiency is increased by up to $7 \%$, permitting a reduction in fleet size and in operating costs;

## B. Class I AVM. No Modification to Uxban Environment

1. Officer update. Vehicle location data may be encoded automatically by means of manually operated devices installed in the vehicle, such as keyboards or stylus maps.
a. Keyboard entry. This manual data input technique for providing automatic vehicle location data at the base requires the officer to enter some code or identifying numerical sequence on a digital keyboard (Fig. 1-1). The keyboard can be either the device being used for sending digital messages or a separate unt. The location code can relate to a particular street segment and/or intersection and would probably be four or five digits in length. The vehicle location code is transmitted to the base station either by "Touch-Tone" or some other digital modulation techniques. Volunteer or random-access vehicle polling is most suitable for this technique. The AVM system accuracy is dependent on the code used; that is, either (1) the nearest intersection if only streets or intersections have codes, (2) a particular block on a street if each segment is coded, or (3) the location in a block if street segment is followed by address digits of closest property parcel. The automatic computational requirement is a table look-up function to translate the code to a geographical location. While this AVM technique is low in cost, particularly if a digital message entry device (DiMED) is already installed, it is extremely slow and requires much memorization on the part of the patrolling officers. If the car is out of the normal beat, either a map or street guide would have to be used by the officer for reference to determine the code.


Fig. 1-1. Class I AVM Officer Update Option, Using Keyboard Entry
b. Stylus map. This officer update technique is a manual method whereby the patrolling officer indicates his vehicle's location by pressing the appropriate spot on a special map (Fig. 1-2) with a stylus. The map-and-holder combination encodes the spot where the pressure 15 applied, and the digital code is sent to the base station. The location polling process can be either in response to a request or volunteered
as part of a transmission from the vehicle. Location accuracy is dependent on the scale of the map and on the holder encoding technique. For example, a $20 \times 25 \mathrm{~cm}(8 \times 10 \mathrm{~m}$.) portion of a 7. 5-minute U.S. Geological Survey topographic map (scale 124000 ) would cover an area of 6 x $4.8 \mathrm{~km}(3.6 \times 3 \mathrm{mi})$. If this information were encoded by 5 binary bits ( 1 in 32) on each axıs for a lo-bit location code, then the location could be achieved within a rectangle of about $190 \times 150$ meters ( $600 \times 500 \mathrm{ft}$ ). By increasing the encoding to 12 bits or using a map with half the scale, the size of the vehicle's location rectangle could be decreased by one-half in each dimension. Maps of other beats would probably be requared by each officer together with some means of identifying when these maps were in use. The base station computation requirement is a table look-up function to translate the code to a geographical location.


## VEHICLE EQUIPMENT $\$ 2500$ INSTALLATION \$ 35

Fig. 1-2. Class I AVM Officer Update Option, Using Stylus Map
2. Kinematic sensors. Changes in vehicle location may be sensed either by accelerometers, velocameters, or odometers.
a. Two accelerometers. Dead reckoning, which can measure the change in location of a vehicle, can be mechanized with two accelerometers (Fig, 1-3). These devices would measure the rate of change of velocity of the vehicle in the horizontal plane of the vehicle in both the fore-and-aft and sideways directions. The outputs of the two accelerometers can be used to compute velocities attained as well as changes in direction and distance during a selected time interval. The computations can be performed on-board the vehicle and the results transmitted to the base station, or the outputs of the accelerometers can be encoded and transmitted directly to the base station.

A U-turn made at a speed of $10 \mathrm{~m} / \mathrm{sec}(23 \mathrm{mph})$ in a 4 -lane street about 18 m ( 60 feet) wide 1 s about the limit of vehicle turning performance. This turn would result in about a $0.8-\mathrm{g}$ indication of lateral motion for just over 3 seconds. If the accelerations are sampled and transmitted every 0.03 second, then the 16 data bits each time would lead to a data rate of $4800 \mathrm{bits} / \mathrm{sec}$. Based on personal rapid transit studies, the "comfort"
zone of vehicle operation is in the less than 0.2-g range. If most accelerations experienced by the vehicle are maintaned in this $0.2-\mathrm{g}$ region, then a $1 \%$ full-scale error during a low-g maneuver causes these normal measurements to be in error by $4 \%$ or more.
b. Orthogonal laser velocimeters. This kinematic sensor technique is based on prior work by G. Stavis (Ref. 1), which used a laser velocimeter (Fig. 1-4) and compass (Fig. 1-5). In this scheme, the laser would be used to measure not only the forward velocity of the vehicle, but also that velocity component which occurs during turns and is at a right angle to the fore-and-aft motion. All portions of the vehicle which are not located on the turning axis experience some side velocity during a turn. The sign and magnitude of this velocity component is a function of the distance from and location with respect to the turning axis. If both forward and side velocithes are measured at the same point remote from the turning radus, then the velocities at this point provide a means to keep track of the vehicle motion. The operation of the laser velocimeter is based on the speckle pattern observed in the reflection of coherent laser light from a surface that moves relative to the source. The speckles tend to move in the opposite direction to the relative motion between the laser source and the reflecting surface. By passing the reflected laser light through a diffraction grating and then to a photodetector, a signal can be deraved with a frequency that is a direct measure of the velocity of the reflecting surface. The velocity measured is that at right angles to the rulings on the grating. Two photo detectors and two gratings with the rulings at right angles provide the means to measure the two components of motion of a single laser spot. Investigators in the cited work (Ref. 1) indıcate that a laser velocimeter's dynamic range is of the order of 2500 to $l$ and that the maximum and minimum measurable velocities are primarily a function of the rulings on the grating. For example, a vehicle velocity range of $50 \mathrm{~m} / \mathrm{sec}$ to $2 \mathrm{~cm} / \mathrm{sec}$ ( 115 mph to 0.05 mph ) could be accommodated, and turning rates of 0.01 $\mathrm{radian} / \mathrm{sec}\left(0.6^{\circ} / \mathrm{s}\right)$ could be detected. Maximum data bit rates of about $5000 / \mathrm{sec}$ for speed and $100 / \mathrm{sec}$ for turning may require in-vehicle computation.
c. Ultrasonic velocimeters. The use of ultrasonic waves for intrusion detectors, motion sensors, and distance measuring is well established. The doppler frequency shift of a reflected sound wave from the road surface can form the basis of a velocimeter (Fig. 1-6). An ultrasonic wave directed at an angle at the road surface will reflect a doppler-shifted frequency proportional to the cosine of the angle of incidence times the surface velocity. For example, if a $33-\mathrm{kHz}$ frequency is chosen which has a wave length of about 1 cm directed at a 45 -degree angle to the road surface and traveling at $50 \mathrm{~m} / \mathrm{sec}$ ( 115 mph ) will yield a doppler shift of about $10 \%$. If a dynamic range of $2000: 1$ can be achieved, a minmum velocity of $2.5 \mathrm{~cm} / \mathrm{sec}(0.05 \mathrm{mph}) \mathrm{can}$ be detected. If the velocimeters are mounted on each side of the vehicle and the differential velocities are measured to the same $2.5 \mathrm{~cm} / \mathrm{sec}$, then minimal directional changes of 12 mrad (about 0.7 deg) can be detected. This precision is on the order of that achieved with the differential odometer, described later.

VEhicle


VEHICLE EQUIPMENT $\$ 400$
INSTALLATION $\$ 100$

Fig. 1-3. Class I AVM Kınematic Sensor Using Two Accelerometers


Fig. 1-5. Class I AVM Magnetic Compass with Laser Velocmeter

d. Odometer-Compass. Dead reckoning with compass and odometer (Fig. 1-7) has been tested, built and furnished to several armed forces (U.S., Canada, Britain) as a means of keeping track of military vehicles in off-road situations. The systems have all achieved some measure of success, and all have included onboard computation to indicate position in northings and eastings ( Y - and X-coordinates). Accuracies within 0.6 to $2 \%$ of the distance travelled have been demonstrated. Error sources are the inaccuracies in the odometer measurement and compass heading. The odometer is affected by tread wear and wheel slip maneuvering. Compass heading is influenced by local anomalies, and proposed filtering techniques have included measuring the steering gear angle, vertical component of the field, and limiting direction change as a function of vehicle speed. At present, gyro compasses are not suited for vehicular applications.


VEHICLE EQUIPMENT $\$ 265$
INSTALLATION $\$ 20$

Fig. 1-7. Class I AVM Magnetic Compass with Odometer
3. Wide-area navigation. The three principal wide-area navigation schemes use synchronized radiolocation beacons. They are hyperbolic techniques which operate in three different modes: OMEGA, LORAN, and DECCA.
a. OMEGA. This navigation scheme (Fig. $1-8$ ) uses very low frequency ( $10-13 \mathrm{kHz}$ ) timemultiplexed $R F$ signals. The relative phase of the


VEHICLE EQUIPMENT $\$ 1500$
INSTALLATION \$ 80

Fig. 1-8. Class I AVM Normal and Differential OMEGA Navigation
signals, transmitted on the same frequency in sequence from several sites, defines a set of lines of position (LOP). At the intersection point of the LOPs is the receive location. There are ambiguities in position since the phase patterns repeat every 15 km or so. Differential OMEGA is a technique for reducing the effects of local anomalies. A fixed recelver at a precisely known location is used to remove these anomalies over a 15 to 30 km radius through continuous monitoring of the received signals.
b. Relay OMEGA. In this technique (Fig. 1-9), the vehicle rebroadcasts the raw OMEGA signals on another frequency to the base station. The base station then measures the phase differences and computes the LOPs. This 15 a timeconsuming operation as each vehicle would have to transmit the entire OMEGA sequence lasting several seconds.


VEHICLE EQUIPMENT $\$ 375$
INSTALLATION $\$ 80$

Fig. 1-9. Class I AVM Relay OMEGA Navigation System
c. LORAN. This technique (F2g. 1-10) uses combined pulse and phase time-multiplexed RF signals for determining LOPs. Pulsed signals from three or more stations are transmitted 10 to


## VEHICLE EQUIPMENT $\$ 2600$

INSTALLATION \$ 80

Fig. 1-10. Class I AVM Normal and Differential LORAN Navigation

33 times a second in coded groups. The receiver measures the time of arrival difference from given pairs of signals to determine the LOP. No ambiguity exısts, and each LOP is unique geographically. Differential LORAN also uses fixed site receivers to remove local propagation anomalies.
d. Relay LORAN. In this system (Fig. 1-11), the recelved signals axe retransmitted to a base station for time differencing. Some bandwidth compréssion is required and is used in a technique called LOCATES in order to retransmit the 90 to 110 kHz LORAN over voice communication channels. The $20-\mathrm{kHz}$ bandwidth signals are reduced to 3 to 7 kFz for retransmission. The higher repetition rates of LORAN make relaying more feasible than in OMEGA.


## VEHICLE EQUIPMENT $\$ 425$ INSTALLATION $\$ 80$

Fig. 1-11. Class I AVM Relay LORAN Navigation System
e. DECCA. The DECCA system (Fig.

1-12) is a continuous-wave phase-difference technique in which each transmitter operates on a different, but harmonically related, signal to other transmitters. The location is determmed by simultaneous reception and comparison of the phase of the signals. Since the LOPs determined by the phase measurements are not unique, speclal signals are transmitted frequently to enable the determination of the correct one.

# VEHICLE EQUIPMENT \$950 

INSTALLATION \$ 60

Fig. 1-12. Class I AVM DECCA Navigation System
f. AM Broadcasting stations as radiolocation beacons. Carrier signal frequencies, being transmitted from three commercial broadcasting stations located around a city's perimeter, can each be separately received and multiplied by relatively low-cost in-vehicle equipment to synthesize a new common frequency. These three 1dentical frequencies can be made relatively phase coherent. Virtual hyperbolic patterns of navigathonal LOPs are generated by the signals received
from each pair of AM stations. These LOPs can serve as the basis for a reliable AVM system (Fig. 1-13). A vehicle's starting position is first noted and recorded at the central command base. When the vehicle moves, the phase differences produced in the three signal frequencies are measured on-board, and the number of times that the phase pattern is repeated can be counted on-board. This digital information is then sent to the base where a minicomputer converts it to the vehicles new geographical location. In Part Four of this report, this AVM system is described in detall.


|  | NORMAL | DIFFERENTIAL |
| ---: | :---: | :---: |
| VEHICLE EQUIPMENT | $\$ 200$ | $\$ 315$ |
| INSTALLATION | $\$ 50$ |  |

Fig. 1-13. Class I AVM AM Broadcasting Station Navigation Systems

## C. Class II AVM: Autonomous Signposts Throughout Urban Area

All autonomous signpost location techniques rely on the vehicle coming near or passing over an instrumented geographical location. The instrument, located at an intersection or road segment, is usually a continuously radiating device sending out a uniquely coded message, either radio, light, IR, ultrasound, or magnetic. The vehicle is equipped with a suitable receptor to receive and store the message for subsequent retransmission to the base station and in this way inform the base as to the last instrumented location passed.

1. Radio frequency signposts. Most of the techniques use RF signals as the medium for the short-range link from wayside or roadway signpost to vehicle. These signals, which may range from low frequencies ( 190 kHz ) through VHF to X-band ( 10 GHz ), require the equipment shown in Figs. 1-14, 1-15, 1-16. Elevated locations for the signposts are usually selected to achieve a larger coverage area, freedom from blocking by large vehicles, and to lessen the probability of vandalism. Vehicle location accuracies of the Class II AVM systems are a function of the radius of influence and density of the signposts, and similarly the message repetition rate from the post must increase as the radus of influence decreases to ensure complete message reception by a fast moving vehicle.

$\infty$

$$
\begin{aligned}
\text { VEHICLE EQUIPMENT } & \$ 100 \\
\text { INSTALLATION } & \$ 45 \\
\text { FIXED EQUIPMENT } & \$ 125 \\
\text { INSTALLATION } & \$ 45
\end{aligned}
$$

Fig. 1-14. Class II AVM Low-Frequency
Wayside Radio Signposts


VEHICLE EQUIPMENT $\$ 105$
INSTALLATION $\$ 40$
FIXED EQUIPMENT $\$ 100$ INSTALLATION \$ 45

Fig. 1-15. Class II AVM Citizen Band or VHF Wayside Radio Signposts


Fig. 1-16. Class II AVM X-Band Wayside
Radıo Signposts
Since active electronic signposts require some primary power source, difficulties may be encountered in general applacations if reliance is placed on either street lighting circuits or traffic signals In some applications, alternate power sources will be necessary. Options other than utility power are long-lived batteries, solar, and radiolsotope sources.
2. Ultrasonic and photo or IR signposts. Ultrasonic and light radiation are possible practical approaches to the message link to avoid further RF congestion and interference to other services. The ultrasonic waves (Fig. 1-17) are similar in length to X-Band RF (less than 1 cm ), and "horn" antennas can be designed for focusing sound to a desixed coverage area. The flashing light approach (Fig. l-18), either visible or infrared, $1 s$ also a practical short-range information transfer method. Both of these techniques are, however, somewhat hindered by weather conditions, particularly fog, rain, and wind.
3. Buried active antennas. The buried antenna approach using existing traffic-presence sensor loops as electronic signposts (Fig, 1-19) is currently being tested in San Francisco and New York as a toll authority billing technique for equipped buses In these systems, the antenna (buried loop) interrogates continually and receives responses from instrumented buses so that the buses may be billed for toll fees without having to stop. The use of traffic sensor loops as antennas is a practical implementation for electronic signposts and has an added advantage in that weatherproof enclosures and power are available in the traffic signal controller.


VEHICLE EQUIPMENT \$85
INSTALLATION \$85
FIXED EQUIPMENT \$115
INSTALLATION $\$ 45$
Fug. 1-17. Class II AVM Autonomous Ultrasomic Signposts


VEHICLE EQUIPMENT \$95
INSTALLATION \$75
FIXED EQUIPMENT $\$ 100$
INSTALLATION \$55
Fig. 1-18. Class II AVM Flashing Visible or IR Light Signposts


VEHICLE EQUIPMENT \$ 95 INSTALLATION $\$ 40$ FIXED EQUIPMENT $\$ 100$ INSTALLATION \$ 20

Fig. 1-19. Class II AVM Actıve Buried Antenna Traffic Sensors
4. Buried magnet autonomous location 1 dentifiers. Buried permanent magnets are used to provide a means of passive proximity location identification (Fig. 1-20). In this concept, rows of permanent magnets are installed along vehicle lanes to provide a means of inducing a voltage in a sensing coil mounted on the vehicle. The magnets could be either placed in drilled holes in the - pavement or propelled into the surface by using an explosive-actuated concrete fastener tool. Magnets in the rows have exther $N$ or $S$ poles up to provide binary identification of the location. The sense coil in a forward moving vehicle would detect signals of different polarities depending on the vehicle direction across the magnetic field. Reasonably strong magnets must be used, both to be detected in the presence of the earth's field, which is about 0.5 gauss, and to withstand added spacing that could be created by street resurfacing.


Fig. 1-20. Class II AVM Buried Magnets as Location Identifiers
5. Reflective paint patterns on signposts and roadways. Other passive techniques require that the vehicle continually interrogate the area travelled either by low-frequency $R F$ or light radiation. In the case of the reflective wayside sign (Fig. 1-21) or pattern on the road (Fig. 1-22), the vehicle must be in a fairly precise position to
receive a response- less in the case of the road pattern than the wayside sign.


VEHKLE EQUIPMENT \$ 75
INSTALLATION \$ 60
FIXED EQUIPMENT \$ 5
INSTALLATION $\$ 120$
Fig. 1-22. Class II AVM Sensor of Reflective Patterns on Roadway
6. Passive buried loops. The passive buried loop (Fig. l-23) requires that the vehicle, equipped with under-car antennas, pass over and excite the loops to obtain a response. Results of a detailed analysis of the bursed loop coupling are included in Part Four of this report.

## D. Class III AVM. Sparsely Distributed Special RF Sites

This class of AVM systems encompasses those vehicle location techniques of the trilateration rho-rho (range-range) and triangulation thetatheta (angle-angle) types with sparsely dustributed RF sites primarily intended for medium or small urban area coverage, 7 km ( 4 mi ) to $11 \mathrm{~km}(7 \mathrm{mz}$ ) radius.

1. Trilateration Systems. Included in the rho-rho systems are trilateration techniques which measure the time-of-arrival (IOA) of a . signal emanating from a vehicle at several fixed recelving sites. Each pair of time differences


VEHKLE EQUIPMENJ $\$ 90$ INSTALLATION \$45 FIXED EQUIPMENT $\$ 10$ ( $\$ 2$ LOOP) INSTALLATION SB/LANE ( $\$ 17 / L O O P$ )

Fig. 1-23 Class II AVM Sensor of Passive Buried Resonant Loops
forms a hyperbolic line-of-position (LOP). The intersection of these LOPs establishes the position of the vehicle. This information may be sent to the base station from the site by leased telephone lines or by microwave transmissions.

Hyperbolic trilateration methods tested have used either a pulsed (or keyed) carrier from the vehicle or an audio-tone frequency modulating a carrier. The pulse systems measure the TOA of the signal and establish the range differences directly. The tone trilateration systems measure the relative phase of the audio tone at the recelving sites, and the phase dafference measurement .then determines the range difference.

The tested tone phase TOA trilateration methods used 2.7 kHz and approximately 18 kHz frequencies whose phase patterns repeat at 111 km and 16 km , respectavely. These AVM systems have been termed narrow-band (Fig. 1-24) and wide-band (Fig. 1-25) since the first can be accommodated in a narrow-band FM voice channel ( 25 lfHz ) while the second requires eight times the bandwidth or four adjacent channels ( 100 kHz ). In comparison, the pulse TOA method (Fig. 1-26) utilizes up to 10 MHz of bandwadth to preserve the leading edge of the pulse.

Another wide-band trilateration method is based on interferometer techniques. As currently envisaged, each vehicle would transmit a carrier signal modulated with either white or $\mathrm{P}-\mathrm{N}$ sequence noise (Fig. 1-27). These signals would again be received at the several sites, and by correlation computation the time differences of arrival would be established. Since only the signals from one vehicle would show substantial correlation, it would be possible but not necessary to have all vehicles broadcasting the noise modulated signals simultaneously. The effects of multipath on trilateration techniques have been analyzed and modeled by George Turin (Ref. 5).
2. Triangulation Systems. The direction finding methods proposed would measure the azimuth angle of the vehicle signal at several fixed sites (Fig. 1-28). The intersection of the extension of these bearing angles would be the position of the vehicle. Multipath in this method would probably cause uncertainty in the angle of arrival of the vehicle signal leading to
approximately the same accuracy limitations as those for trilateration. Of the Class III AVM systems delineated, the direction finding and narrow-band phase TOA would allow the use of the normal vehicle transceiver. The pulse, wideband phase, and noise modulation TOA methods would require an additional AVM transmitter.


VEHICLE EQUIPMENT \$ 60
INSTALLATION \$ 40
FIXED SITE EQUIPMENT $\$ 4,500$
INSTALLATION \$ 500
Fig. 1-24. Class III AVM Narrow-Band FM
Phase TOA Trilateration


VEHICLE EQUIPMENT $\$ 2875$ (CUBIC)
INSTALLATION \$ 90
FIXED SITE EQUIPMENT $\$ 9500$ INSTALLATION $\$ 1500$

Fig. 1-25. Class III AVM Wide-Band FM Phase TOA Trilateration


VEHICLE EQUIPMENT \$ 1,285
INSTALLATION \$ 150
FIXED SITE EQUIPMENT $\$ 12,000$ INSTALLATION $\$ 2,500$

Fig. 1-26. Class III AVM Pulse TOA Fixed Site Trilateration


VEHICLE EQUIPMENT $\$ 785$
INSTALLATION \$ 100
FIXED SITE EQUIPMENT $\$ 7500$
INSTALLATION \$1500

Fig. I-27. Class III AVM Nouse Correlation TOA Trilateration


Fig. 1-28. Class III AVM Direction Finding from Special RF Sites

## E. Class IV AVM, Monitored Signposts Throughout Urban Area

This class of AVM techniques is an inversion of the Class II autonomous wayside or buried signposts and removes the data collection link responsibility from the vehicle. In Class IV AVM, a vehicle-to-signpost link (Fig. I-29) is maintaned, but the information flow is the vehicle's identity to the monitored signpost. The data link to the base station or central collection point is based either on telephone lines rented from the local utility of on call-box lanes for police and fire use. Since individual Ines from each signpost are usually not considered economically practical, it is usually proposed to group the signposts on "party lines". The "party line" approach requires that each signpost not only transmit the vehicle ID data recerved but also identify itself to the central collection point at the base station. The telephone line is an additional complication to the Class IV installation, and a prime power connection is still required.

A technique of using the buried loop-sensors, which actuate traffic signals, as receiving antennas (Fig. l-30) can be used in the monitored Class IV as in the autonomous Class II signpost method. This is an especially attractive approach if the signals are centrally controlled because dedicated communication lines are usually already installed. Ultrasonic as well as photo/IR detectors could also be used on monitored signposts (Figs. 1-31, 1-32).


In Class IV, the vehicle polling function is Beplaced either by line-finding, as is used in normal telephone service, or by a continual scanning of the lines to find an "off hook" indication that a signpost on one of the party lines has information to forward.



Fig. I-31. Class IV AVM Monitored Ultrasonic Wave Receptors


Fig. 1-32. Class IV AVM Monitored Photo or IR Detectors

## II. VEHICLE POLLING AND <br> LOCATION PERFORMANCE

## A. Vehicle Polling Techniques and Costs

Four general classes of vehicle polling are considered for AVM Systems: (1) Synchronous, (2) Commanded or random access, (3) Synchronous with command capability, and (4).Volunteer or contention. All four techniques are generally applicable to Class I and II AVM systems. Synchronous polling and synchronous with command are used mainly in Class III AVM systems with sparsely distributed special signposts. Volunteer polling is usually considered only for lowdensity Class II autonomous signpost systems. For the Class IV monitored signpost systems which use land-lines, vehicle polling by radio is not applicable in the context used here.

All of the polling techniques are suitable for half-duplex (base station and vehicle on the same frequency), but when the base station relays all vehicle transmissions or when each vehicle monitors all other vehicles, then volunteer polling can only be used on full-duplex (base and vehicle on different frequencies).

In Class I and II AVM systems where the currently installed 2 -way radio is to be used for AVM purposes, speed-up modifications are required. These changes to antenna switching, transmitter stabilization time, and squelch delay are necessary to reduce the substantial guard time required between transmissions from vehicles adjacent in the polling sequence or to reduce the transition time interval from receive to transmit in Commanded or random access polling.

A modification of the Volunteer polling method only allows location data to be transmitted as a precursor or brief interruption of voice transmissions, but this technıque has limited application. Interrupted speech as a technique in other polling methods relies on very short transmit on-off-on sequences for a vehicle currently using voice when another vehicle responds with data.

1. Synchronous polling. In this technique, each vehicle transmits location data at a preselected time withan the polling sequence. The equipment on the vehicle keeps track of the start of the polling sequence and internally determines when the appropriate time to respond occurs. The functional elements of Synchronous polling are shown in Fig. 1-33. The fact that the start of the polling sequence must be periodically transmitted to each vehicle for correction purposes leads to the capability of the base station to modify the time when the vehrcles are to respond in the polling epoch.
2. Synchronous whth command capability. This technıque allows the base station to modify the position of each vehicle in the polling sequence. The addrtional functional elements for the command option are shown in Fig. 1-34 connected by dashed lines to the elements required for synchronous polling.


$$
\begin{aligned}
& \text { VEHICLE EQUIPMENT ( } \$ 165+\$ 4 n \text { ) } \\
& \text { INSTALLATION } \$ 40 \\
& \text { FAST TURN-ON } \\
& \text { SQUELCH MODIF }
\end{aligned} \mathbf{\$ 5 0} 8
$$

Fig 1-33. Vehicle Synchronized Polling for AVM Classes I, II, III


VEHKCLE EQUIPMENT $\$ 315+54 n$ INSTALLATION $\$ 50$

Fig. 1-34. Vehicle Commanded Polling for AVM Classes I, II, III.
3. Commanded or random access polling. Commanded polling requires that the base station send a request to each vehicle whenever location data is required. This random access technique is the most flexible but requires substantially more use of available RF time than the synchronous method or the synchronous with command capability. The elements required for the commanded polling method are shown in Fig. 1-34.
4. Volunteer polling. This contention method of sending location data requires that each vehicle determine if the channel is "clear" before transmitting. A mechanization is shown in Fig, 1-35. Some technique of providing a random delay in each vehicle after determining that the channel is clear and before transmitting is usually necessary
to preclude certain vehzcles from dominating the channel．


VEHICLE EQUIPMENT $\$ 130+\$$ An INSTALLATION $\$ 30$

Fig．1－35．Vehicle Volunteer Polling for AVM Class II Systems

## B．Vehicle Polling and RF Link Evaluations

The three vehicle polling techniques：Synchro－ nous（SYN），Volunteer（VOL），and Random （RAND）or commanded were evaluated with both a simple one－time radio message transmussion and with redundant transmission，where every message is sent twice．In all cases，the digital message rate is set at 1500 bps ．Where equiva－ lent RF channels are assumed，a channel spacing of 25 kHz is used．

Any delays in the polling processes will tend to reduce the number of vehicles which can be accommodated by an RE channel．Therefore all of the delays are lumped into one parameter called turn－on time．Thirty two of the Class I，II and III AVM techniques were evaluated in both the simple and redundant modes of the three polling methods．The range of turn－on times examined was from 0 to 0.3 second，in five steps．This range is sufficient to estimate the performance of full－duplex radios with separate antenna cir－ cuits relative to half－duplex with electro－ mechanical antenna transfer relays．Tables 1－1 through 1－5 are compilations of the vehicles polled per second per RF channel．Each table includes a theoretical maxmum entry which is the 1500 bps rate divided by the number of bits in the location message．Included under．Class II techniques are small and large entries as the location message length is a function of the number of instrumented intersections，therefore data are provided for both small and large urban areas．Since the Class III techniques in general are not amenable to volunteer（VOL）polling methods，no VOL calculations were made for this class．Also，with the exception of direction finding and narrow－band phase location，trans－ ponder type radio equipment is required which does not have the same order of delays．

Table 1－1．Vehicles Polled／Second／RF Channel For 0 Sec Turn－On

| TEchilloue Caps | PEF SECOHS | RF CHHIINE |  | L．HITH DIFFEFEHT POLL ING |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| ClRSS I | Mfx | Sha | vol | Refd | 5 SH | YOL | Ratid |  |
| KEf SORRD | 137 | 137 | 72 | 72 | 69 | 3 | 30 |  |
| Stylus hap | 34 | 24 | 3 | 5 | －2 | だ | ＜ |  |
| 2－fiLCELEFOHETEPS | 108 | 198 | 63 | 63 | 54 | 32 | 32 |  |
| LHSEP VELOCIITP | 0.4 | 4.9 | 58 | 53 | $7 ?$ | 29 | 27 |  |
| ultarsuhic uela | 143 | 103 | 0 | 63 | 54 | 32 | 32 |  |
| CUIPRES／ODOHETER | tus | $1 \geqslant 3$ | 63 | －3 | 5 | E2 | 32 |  |
| COILPASシLRSEP VEL | 108 | 108 | 63 | 03 | 54 | 32 | 32 |  |
| CIPSSSU－SOHIE יEL | 193 | 1 L | 63 | 63 | 5 | 32 | 32 |  |
| OrECA | 50 | 5 | 41 | 7 | 23 | 21 | 21 |  |
| LURR3 | 47 | $\rightarrow$ | 36 | 36 | 2 | 18 | 18 |  |
| decca | 59 | 50 | $3{ }^{3}$ | 37 | 25 | 19 | 19 |  |
| aty－STATIOHS | 125 | 125 | 89 | 69 | 03 | 3 | 35 |  |
| DIFF OMEGA | 56 | 56 | 41 | 41 | 23 | 21 | 21 |  |
| DIFF LORAI | $\rightarrow 7$ | 47 | 36 | 36 | 24 | 13 | 18 |  |
| DIFF HII－STA | 53 | 58 | 42 | 42 | 23 | 31 | 21 |  |
| PELA＇OTEGR | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| relfis Lerfit | 2 | 3 | 3 | 3 | 2 | 2 | こ | － |
| techitioue | THE0 | SIMPLE |  |  |  | CEEUSDALT |  |  |
| CLASS II | $\mathrm{H}_{1 \mathrm{H}}$ JMLG | $\begin{gathered} \text { SYH } \\ \text { GHLL } \end{gathered}$ | JoL EIVLG | FPHD © $11 / L G$ |  | $5$ | NOL | PRIID |
| EUPIED RES LOOPS | 159 | 150 | 168 | 148 |  |  | $5 \cdot$ | 5 |
|  | 34 | 34 | 57 | 54 |  | ＋ | 27 | 2－ |
| REFLECTIM SIGHS | 156 | 154 | 183 | 108 |  | 75 | 5 | 54 |
|  | 3. | 24 | 5 | 54 |  | 42 | ${ }^{-}$ | 27 |
| REFLECTILIS RGAD | 150 | 150 | 100 | 103 |  | 75 | 5 | 5 |
|  | 8 | 3.4 | 54 | 5. |  | ${ }^{2}$ | 27 | ${ }^{2}$ |
| X－Jing post | $16 \%$ | $10 \stackrel{3}{6}$ | 116 | 110 |  | 64 | S8 | 5 |
|  | 39 | 39 | 5 | 56 |  | 45 | 26 | $\approx$ |
| hFF，UTIF POST | 215 | 615 | 137 | 137 |  | 19 | 69 | 09 |
|  | 168 | 10 u | 60 | 69 |  | 50 | 30 | 30 |
| LF POST | 107 | 167 | 115 | 116 |  | 84 | 5 | 5 |
|  | 39 | C9 | 56 | 56 |  | 45 | 28 | 込 |
| LICHT／I－R FOST | $16 ?$ | 107 | 116 | 116 |  | 云 | 58 | 0 |
|  | ．99 | 69 | 50 | 56 |  | 45 | 2 | － |
| SUPIED IAGGETS | 150 | 150 | 193 | 1 ys |  | 75 | 5 | 5 |
|  | 3. | $\bigcirc$ | 54 | 5 |  | ${ }^{+5}$ | $\underline{ }$ | 2 |
| LRTPHSOHIC POST | 167 | 167 | 116 | 115 |  | 84 | 58 | 5 |
|  | ＊ | 30 | 56 | 56 |  | 45 | ๕ | 2 |
| TPAFFIC SEHISOR | 154 | 150 | 16 | 180 |  | 75 | 54 | $5{ }^{\text {r }}$ |
|  | 3 | 64 | 54 | 54 |  | 42 | 27 | 27 |
| Clfass III |  | CARS PER SECOIDSIMPLE |  |  |  | PEDUIDART |  |  |
|  | 11H RF |  |  |  |  |  |  |  |
| TECHHIPUE | CHRMHELS |  | T72 | PRID |  | STuc |  | Prains |
| MAR－EFATM FH PHASE | 1 |  | 7 | 47 |  | $\stackrel{4}{ }$ |  | ${ }^{2}$ |
| HIp－EALD Fil FHase | 4 | 40 |  | 110 |  | 284 |  | 55 |
| PULSE T－O－ARPIUAL | 400 | 1090 |  | 000 |  | $10 \pm 019$ |  | 10006 |
| HOISE CORRELATION | 263 | 100 |  | 000 |  | 1 リ011 |  | 108 |
| DIRECTIOH FINDER | 1 |  | 5 | 5 |  | － |  | 3 |

Table I－2．Vehicles Polled／Second／RF Channel For 0．01－Sec Turn－On


Table 1-3. Vehxcles Polled/Second/RF Channel For 0.03-Sec Turn-On


| ELASS III | CAFS FEP SECOHD |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| techinoue | CHATHIELS | - | Retil | S.llc | 6. $\mathrm{CH}^{\text {d }}$ |
| NHP-3819 FH1 PHASE | 1 | 2 | 30 | 17 | 17 |
|  | 4 | 31 | 26 | 29 | 21 |
| PLLSE T-U-HRRIUAL | 400 | 1000t | 10908 | 10000 | 18000 |
| WOISE CORRELATIOH | 200 | 1009 | 1809 | 10 e | 1600 |
| DIRECTION FINDER | , | 5 | 5 | 3 |  |

Table 1-4. Vehicles Polled/Second/RF Channel For 0.1mSec Turn-On


Table 1-5. Vehicles Polled/Second/RF Channel For 0.3 Sec Turn-On


Message lengths of most vehicle polling techniques are about 20 bits or occupy about $15 \mathrm{mil}-$ liseconds or less of transmission tume at the selected bit rate. Turn-on times of this order will therefore reduce the achievable polling rate to less than half the theoretical value. Turn-on times quickly dominate the polling rates at values above 0.03 second.

Class IV AVM systems, with monitored signposts, do not require radio polling. The vehicle polling function is replaced either by line findung, as is used in "normal" telephone service, or by a continual scanning of "party lines" to find an "off-hook" indication on one of the party lines that one of a group of signposts has some information to forward regarding the ID of a fleet vehicle that is passing its vicinyty.

## C. Location Performance Parameters

Several technical performance parameters of individual vehicle location techniques, including accuracy, quantity of location data, and fix time, affect both the design and expected performance of complete AVM systems. Accuracy of the location information is the parameter which usually elicits the most interest. This ultimate achievable accuracy for a given technique is, however, almost always degraded when the technigue is configured into an AVM system. The reduction in location accuracy is caused by the vehicle's motion, the delay in vehicle-to-base transmission, the computer processing time to relate the vehicle data received to a physical location, and
the delay in displaying the location on a map or other computer output device. In dead-reckoning systems, the location error is cumulative, and the accuracy is proportioned to a percentage of the distance travelled (\% dist).

The amount of location data which must be sent to or from the vehicle is another parameter that affects performance. Not only is it a function of the location technique, but also of the number of vehicles in the system, the area of the urban coverage, the density of streets or intersections in the area, and the dimensions of the urban area in each direction. The quantity of location data, together with the polling technique used and the avarlability of RF channels, determines the delays in recesving vehicle data at the base, which in turn affects the AVM system accuracy.

Another parameter is the "fyx" time required for the vehicle to recelve or generate whatever raw data is required for the new location to be determined elsewhere, which is primarily techmque dependent. Similarly the interval between successive messages from the vehicle is also techmque dependent. That is, no new location information will be forthcoming until a definite time period or travelled distance has elapsed or has been accumulated.

A tabular compilation of four location performance characteristics has been developed from several sources such as test data, prototype demonstrations, and performance estimates by both system developers and other evaluators. In Table 1-6, the performance values for the location accuracy or radus, the amount of location data, and the fix time parameters are listed for the four AVM classes and 36 systems. An explanation of each parameter follows:

1. Accuracy. This tabular entry represents elther the estimated or test-result accuracy of vehicle location for Class I and Class III AVM systems. Since the accuracy cannot always be stated as a single value, a range of values is given in some cases. In the case of Class II and IV signpost systems, the term accuracy 15 inappropriate, and the term radius is used.
2. Radius, In Class II, III, and IV AVM systems, this radus figure represents the estimated coverage of the individual signpost or the special purpose fixed site.
3. Fix time. This value is the time in seconds required for the vehicle to receive or generate new location data. In Class I AVM systems, the fix time is determined by the updating rate of the vehicle sensors or the repetition rate of the navigational aid. In Class II or IV systems, the fix time is a comparative number only and represents the time interval required such that a vehicle near the sagnpost will receive at least two location messages while moving at a speed of $50 \mathrm{~m} / \mathrm{sec}$ ( 113 mph ). In Class III systems, the fix time represents only the time of transmission of a location signal from the vehicle to the special RF site.
4. Location data. This tabulated number represents the minimum quantity of raw data required to locate an individual vehicle. In Class I AVM dead-reckoning methods, the location data figure is the combined number of bits required to represent a change in vehicle position to the indicated accuracy. In Class I navigational alds, the figure is exther the number of bits required to indicate the time or phase differences of the received signals or the actual RF bandwidth (BW) required in the relay systems. In Class II or IV AVM systems, the location data value is the number of bits required to uniquely identify each signpost or each vehicle, respectively. The Class III location data is the RF bandwidth required for the tone, pulse, or noise location signal.

## III. UREAN CHARACTERISTICS THAT AFFECT AVM COSTS

A. City Model Parameters For AVM System Design

In order to develop a basis for AVM System cost comparisons, it was necessary to establish baseline system design parameters applicable to each technique. To make these designs somewhat realistic, three model cities were developed, based on the populations and physicalparameters of the seven representative UGAC cities in Southern California. Characteristics of the small, medium, and large model city are given in Table 1-7. The justification or rationalization for the model city parameters and the other factors considered in the system design are as follows.

1. Gity Shape. One characteristic of the model cities that 1 s difficult to justify is shape. In this Report, the assumption is made that the cities are rectangular with a 2 -to- 1 aspect ratio. The development of most cities either along a river, ranlway, or coastal harbor usually results in one dimension being significantly greater than the other. The chorce of a rectangle is believed to be more realistic than the square or circular city sometimes chosen.
2. Urban area. The areas chosen for the three city models are 10,100 , and $1000 \mathrm{~km}^{2}$ ( 4,40 , and $400 \mathrm{mi}^{2}$ ), which compare with Montclair and Monterey Park as the smallest cities, Anaheim, Pasadena, and Long Beach as the medrum cities, and Los Angeles and San Diego as the large cities. (See Part Two of this Report, p. 2-1.)
3. Population. The populations of the model cities are based on population densities in the actual cities, which average 3000 people per square kilometer ( $7800 / \mathrm{mi}^{2}$ ).
4. Vehicle fleet size. Two classifications of vehicles are assumed for each city. These are the patrolling vehicles and the total number of instrumented vehicles. An assumption is made that one-half the fleet is patrolling while the remainder is involved in investigation.

Table 1-6. Location Performance Parameters for All AVM Classes and Systems

| Technıque | Accuracy or Radius | $\begin{aligned} & \text { Value used, } \\ & (\mathrm{m}) \end{aligned}$ | Location Data, bits or BW | Fix Time, sec |
| :---: | :---: | :---: | :---: | :---: |
| CLASS I AVM <br> Keyboard update Stylus map update 2-Accelerometers Laser velocimtr Ultrasonic velo Compass/odometer Compass/laser vel Cmpss/u-sonic vel OMEGA navigation LORAN navigation DECCA navigation AM-Stations nav Diff OMEGA nav Diff LORAN nav Diff AM-Stations Relay OMEGA nav Relay LORAN nav | Accuracy <br> 10-100 m <br> 30 m <br> $2 \%$ dist <br> $0.5 \%$ dist <br> $3 \%$ dist <br> $1 \%$ dist <br> $0.6 \%$ dist <br> $0.8 \%$ dist <br> 1600 m <br> $0.4 \mathrm{~m} / \mathrm{km}$ <br> $0.5 \mathrm{~m} / \mathrm{km}$ <br> $150-250 \mathrm{~m}$ <br> 160 m <br> $120-400 \mathrm{~m}$ <br> $150-250 \mathrm{~m}$ <br> 200-600 m <br> 800 m | (33) <br> (30) <br> (34) <br> (13) <br> (40) <br> (20) <br> (15) <br> (17) <br> (1600) <br> (160) <br> (200) <br> (200) <br> (160) <br> (400) <br> (250) <br> (500) <br> (800) | $\begin{aligned} & 6-20 \text { bits } \\ & 14-20 \\ & 14 \\ & 16 \\ & 14 \\ & 14 \\ & 14 \\ & 14 \\ & 27 \\ & 32 \\ & 30 \\ & 12 \\ & 27 \\ & 32 \\ & 21-32 \\ & 3 \mathrm{kHz} \mathrm{BW} \\ & 10 \mathrm{kHz} \mathrm{BW} \end{aligned}$ | $\begin{aligned} & 2-5 \mathrm{~s} \\ & 3 \\ & 0.3 \\ & 0.3 \\ & 0.3 \\ & 0.3 \\ & 0.3 \\ & 0.3 \\ & 3-10 \\ & 0.06-.2 \\ & 0 \\ & 0-3 \\ & 3-10 \\ & 0.06-.2 \\ & 0-3 \\ & 3-10 \\ & 0.06-.2 \end{aligned}$ |
| CLASS II AVM <br> Buried res loops <br> Reflecting signs Reflecting road X-Band signposts HF, VHF signpost LF Signposts Light/IR post Buried magnets Ultrasonic post Traffic sensor | $\begin{aligned} & \text { Raduus } \mathrm{m} \\ & 10 \\ & 10 \\ & 3 \\ & 12-100 \\ & 15-100 \\ & 100 \\ & 30 \\ & 10 \\ & 20 \\ & 10 \end{aligned}$ |  | $\begin{aligned} & 10-18 \text { bits } \\ & 10-18 \\ & 10-18 \\ & 9-17 \\ & 7-15 \\ & 9-17 \\ & 9-17 \\ & 10-18 \\ & 9-17 \\ & 10-18 \end{aligned}$ | $\begin{aligned} & 1-2 \mathrm{~s} \\ & 1-2 \\ & 1-2 \\ & 1-2 \\ & 2-5 \\ & 1-2 \\ & 1-2 \\ & 1-2 \\ & 1-2 \\ & 1-2 \end{aligned}$ |
| CLASS III AVM <br> Nar-band FM phase Wid-band FM phase Pulse T-O-Arrival Norse correlation Direction finder | Accuracy <br> 800-1300 m <br> 1000-1500 <br> 100 m <br> 100 m <br> $3 \%$ dist | $\begin{aligned} & (1000) \\ & (1200) \\ & (100) \\ & (100) \\ & (700) \end{aligned}$ | $\begin{aligned} & 3 \mathrm{kFz} \mathrm{BW} \\ & 15-40 \mathrm{kHz} \\ & 10 \mathrm{MHz} \\ & 5-10 \mathrm{MHz} \\ & 3 \mathrm{kHz} \end{aligned}$ | $\begin{aligned} & 0.015 \mathrm{~s} \\ & 0.01 \\ & 0.0001 \\ & 0.001 \\ & 0.2 .1 \end{aligned}$ |
| CLASS IV AVM <br> Traffic loops Wayside radio Photo/IR detect Ultrasonic detect | $\begin{aligned} & \text { Radius, m } \\ & 10 \\ & 100 \\ & 30 \\ & 20 \end{aligned}$ |  | $\begin{aligned} & \text { N/A } \\ & \text { N/A } \\ & \text { N/A } \\ & \text { N/A } \end{aligned}$ | $\begin{aligned} & 1-2 s \\ & 1-2 \\ & 1-2 \\ & 1-2 \end{aligned}$ |

Table 1-7. Model City Parameters That Affect AVM Costs

| Parameter | Small | Medium | Large |
| :--- | :---: | :---: | :---: |
| Area, km |  |  |  |
| Dimensions, km | 10 | 100 | 1000 |
| Vehicles, patrol/total | $2.2 \times 4.5$ | $7.1 \times 14.2$ | $22.3 \times 44.7$ |
| Intersections* | $5 / 10$ | $50 / 100$ | $500 / 1000$ |
| Road segments $\times$ lanes | 350 | 3500 | 35000 |
| Road distance, km | 1600 | 16800 | 168000 |
| Telephone lines, km | 125 | 828 | 12450 |
| Population | 83 | 300,000 | 8275 |
| *Based on $25 / 75 \%$ ratio of $50 / 30$ blocks $/ \mathrm{km}^{2}$ in the urban area. | $3,000,000$ |  |  |

5．Intersections．The number of intersections in each city is based on two business area street densities．They are based on actual measure－ ments of randomly selected areas of the UGGAC cities，and the values assumed are $30 / \mathrm{km}^{2}$ for $75 \%$ of the area and $50 / \mathrm{km}^{2}$ for $25 \%$ of the area．

6．Road distance．For the purposes of the models，the blocks are assumed to have the same aspect ratio as the city，namely $2: 1$ ，and to be in a regular array．An average of 2.4 lanes for each road segment was assumed，based on UGAC city averages．

7．Telephone line distance，Class IV AVM systems require land line monitoring；and for the purposes of comparison，an equal division of sensors is assumed of up to a maximum of 100 sensors for each phone＂party＂line．These party lines are assumed to parallel the long streets so that the total mileage of lines is about two thirds of the total road distance．

8．Buildang distribution and topography．A uniform low－rise building distribution is assumed for location accuracy comparison purposes．The topography of the model cities is assumed to be essentially flat without＂blind＂radio areas or special areas that might unduly affect any particu－ lar technıque．

9．Radio．The only information sent from the vehicle in this comparison is that required for location，exther as a binary message or equiva－ lent RF bandwidth for the Class I，II，and III systems．Radio modifications are also assumed to enable automatic message transmission． Additıonally，transmitter turn on stabilization time，squelch delay，and antenna transfer are assumed constant at several values．

10．Model city AVM cost and performance summaries．Tables 1－8 through 1－16 summarize the AVM system costs in each of three model cities，small，medrum，and large，for each of thirty six location techniques and for three polling methods．
a．Small city summary．The costs of all AVM techniques in the small city model are dominated by the operation－and－mantenance （ $O-M$ ）cost with the result that there is a great similaraty in total costs regardless of the vehicle location technique．The Class II and IV system costs are higher because the signposts and the associated costs are relatively greater than the vehicle costs（see Tables 1－8，1－9，1－10）．
b．Medium city summary．The costs of AVM Class I in the medium city model show an increase which is almost all due to vehicular equipment．The Class II costs increase by a greater factor due again to signposts．The site costs of the buried resonant loops are substan－ tially higher than those of any other Class II technique because of installation costs．The more sparsely distributed RF posts，exther HF or VHF，do not impact the total cost to the extent of the techniques which use a post at each inter－ section．In the Class III techniques that require pulse or wideband equipment，the vehicular equip－ ment accounts for about one－third the total cost．

In Class IV techniques，the telephone line rental which is included in the site cost is the primary cost factor（see Tables 1－11，1－12，1－13）．
c．Large city summary：The AVM costs in the large model city show the same trend with Class II techniques（save for two exceptions） costing some 2 to 4 times the Class I techniques and about twice the cost of Class III systems． The Class II technıques systems costs are reduc－ able by less dense placement of posts（see Tables 1－14，1－15，1－16）．

The method of vehicle polling has only a slight impact on AVM system costs in any of the tech－ niques in any of the model cities．Applications of the AVM cost analysis to actual cities in Southern California are presented in Part Two of this Report（p．2－1）．

## B．Small Model City AVM Cost Summary Tables

Table－1－8．Small Model City Parameters Used in AVM Cost Analysis

RPEA IS 4 STHAFE MILES．
EASt hest jistarice is 1.4 Hiles．
MOPTH EOUTH IISTATICE IS z．ミ HILES．

TOTAL ROAD HILEAGE $1 今$ 「7 HILES．
THE HUNEEF OF IHTERSECTIOHS IS 3FG：
THE ESTIMATEI HUIREP OF ROAD sEGIEHTS 15 Tog．
Thepe ffe 10 ChPs in the fleet
find there afe g motopc icles．

THE HMISER OF vEHICLES ON ERCH SHIFT IS：


TIRST SHIFT MIII． 5
JECOHID EHIFT MAX． 5

SELOHD SHIFT HIM． 5

THIFD EHIFT HRY 5
THIRD SHIFT MIN． 5

THE GIT＇HOULD PEOUIRE 4 IIDE－BAHID OR
PULSE T－G－A FITTENIA SITES ANI 6 HARPON
shat antenta sites with 7 hid 3 hile couerage fadil．

Table 1－9．Small Model City AVM Cost Summary

| SMALL IODEL CITY CLITSS 1 |  |  |  |  |  | Totals |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | THOUS | HDS 95 |  |  |  |  |  |
| TECHHIOUE | CARS | SITES | EASE | IHST | 0－71 | HOL | Siltc | FRHDCH |
| KEYEORRD | 2 | 0 | 44 | 11 | 101 | 158 | 150 | 156 |
| STYLUS MAP | 26 | 0 | 4 | 11 | 101 | 18 | 18 t | 181 |
| 2－flCCELEROMETEFS | 15 | 6 | 08 | 11 | 101 | 198 | 300 | 208 |
| LFISEP UELOCIMTR | 18 | 0 | 09 | 12 | 102 | 202 | 204 | 203 |
| UTRASOHIC VELO | 13 | 9 | 09 | 11 | 108 | 190 | 1\％3 | 148 |
| COHPASS－ODOMETER | 15 | 0 | 69 | 11 | 181 | 190 | 197 | 180 |
| CWMPASS／LASEP UEL | 19 | 0 | 69 | 12 | 101 | 202 | 204 | 243 |
| CIPSSU－SCHIC UEL | 16 | $\theta$ | 69 | 11 | 101 | 190 | 281 | 200 |
| OHECs | 27 | 8 | 54 | 11 | 101 | 195 | 197 | 177 |
| LOPFM | 28 | 0 | 54 | 11 | 141 | 190 | 198 | 138 |
| DECCA | 12 | 0 | 5.4 | 11 | 101 | 179 | 1洔 | 121 |
| fli－stations | 4 | 8 | 5. | 11 | 101 | 171 | 173 | 172 |
| Diff OHEGA | 27 | $\theta$ | 54 | 11 | 101 | 155 | 197 | 177 |
| DIFF LUNFA | 28 | 0 | 54 | 11 | 101 | 146 | 1508 | 198 |
| DIFF AH－Sta | 5 | $\bigcirc$ | 54 | 11 | 161 | 172 | 17. | 175 |
| pelay ohicga | 0 | 0 | 3.4 | 11 | 191 | 170 | 172 | 176 |
| PELAi LOFFin | 6 | 0 | 5 | 11 | 191 | 174 | 172 | 176 |
| CLISS 11 |  |  |  |  |  |  |  |  |
| Eapled PES L00ps | $\Sigma$ | 108 | 4 | 297 | 101 | 612 | 615 | 610 |
| REFLECTIMG SICHS | 5 | 77 | 44 | 54 | 100 | 289 | 290 | 285 |
| PEFLECTIHC ROAD | 2 | 9 | 44 | 01 | $1 \cdot 3$ | 259 | 264 | 057 |
| －EFALD POST | 2 | 81 | 4 | 27 | 146 | 300 | 261 | 258 |
| HF，UHFP POST | こ | 9 | 4 | 15 | 102 | 172 | 173 | 171 |
| LF FUST | ＊ | 4 | 44 | 37 | 106 | 223 | 224 | ¢ ${ }^{1}$ |
| LIGHT／1－F POST | 2 | 35 | 4 | 30 | 190 | 222 | 222 | 220 |
| PURIED MARSIETS | 1 | 17 | 7 | 45 | 1 ¢ | 2u8 | 204 | 255 |
| ULTFASOHIC POST | 2 | \％ | 4 | 71 | 198 | 265 | 285 | 203 |
| TFAFFIC SEHSOR | 2 | $8{ }^{5}$ | 44 | 59 | 161 | 253 | 253 | 251 |
| CLASS 111 |  |  |  |  |  |  |  |  |
| LIAR－SARIS FII PHASE | 3 | 29 | 57 | 12 | 164 | 023 | 205 | 295 |
|  | 39 | 47 | 69 | 17 | 203 | 3 | 387 | 307 |
| PULSE T－0－AEPPIVAL | 28 | 84 | 139 | 27 | 179 | ． 5.4 | 45 b | 757 |
| HOISE CORFELATIOH | 8 | 29 | 139 | 10 | 177 | 370 | 371 | 371 |
| DIPECTIOH FINIER | 1 | 79 | 34 | 15 | 154 | 232 | 281 | －21 |
| CLASS IU |  |  |  |  |  |  |  |  |
| TPRFFIC LOOPS | 1 | $2{ }^{(10}$ | 4.4 | 186 | 169 | 462 | 462 | 4ne |
| UHTSIDE PADIU | 1 | 170 | 44 | 9 | 118 | 422 | $4{ }^{6} 2$ | 425 |
| PHOTO－I－R DETECT | e | 99 | 4 | 51 | 199 | 363 | 303 | 343 |
| ULTFFSONIC DETECT | 2 | 103 | 4 | 51 | 109 | 397 | 367 | 397 |

Table 1－10．Small City V ehıcle Polling



C．Medium Model City AVM Cost Summary Tables
Table 1－11．Medium Model City Parameters Used in AVM Cost Analysis
AREA is 40 sOUHPE HILES．

EAİT hest jistance is 4.41 hiles．

HORTH SOUTH IISTAICE IS G． 62 hiles．
total poris hilefge is 774 hiles．

THE IUUIRER OF INTERSECTIONS IS 3500：
the citimated number of rahd segments is zgog．

THERE RRE 100 CARS III THE FLEET
fing thepe rpe o notorcycles．
the futter of vehicles oh erch shift is：

FIF 3T SHIFT HAK． 50

FIFST GHIFT IIII． 50

ЗECOII \＃HIFT IARX． 59

SECOHII SHIFT IIIM． 59

THIET SHIFT INFX．SH

THIFI SHIFT IIII． 50

## THE CIT HOLLD REOUIRE 5 HIDE－BAHID OF

FULSE T－G－A FIITEINA SITES AIID 10 NRFRGI

EAIUI AIITENHA SITES WITH 7 FHID 3 IIILE COUERRGE RRADII．

Table 1－12．Medium Model City AVM Cost Summary

| HEDIUR HONEL CIT， |  |  |  |  |  | TOTHLS |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | SITES | ORSE | INST |  |  |  |  |
| VEISOMPI | 17 | － | ORSE | $\xrightarrow[1 \rightarrow]{4}$ | 10ci | 10 L | SHC | Ffidiot |
| ST，LUE MiAP | 25s | $\square$ | $\mathrm{o}^{-}$ | 1 | 100 | 454 | 436 | －3 |
| 2－MCLELEFOHETERS | 160 | 9 | 家 | 4 | 115 | ふ－6 | 412 | $\rightarrow 13$ |
| LASER UELOCIHTP | 173 | 0 | 102 | 27 | 115 | 45 | 455 | 450 |
| ULTPASOUIIC VELO | 127 | ${ }^{\circ}$ | 114 | 2¢ | 115 | 30 | the | 395 |
| COIPPASS／ODOITETER | 147 | 9 | 162 | 12 | 16 | 331 | 465 | 395 |
| COIFHSS／LRSEP UEL | 186 | ด | 102 | 23 | 109 | 438 | － 6 ？ | 452 |
| CHFSSM－SOHIC JEL | 159 | 0 | 192 | 20 | 199 | 40 | 430 | $\rightarrow 2$ |
| UKECR | 2 za | 9 | $\square 7$ | 18 | 168 | 499 | 525 | 519 |
| LOPFIH | 200 | 9 | 37 | 15 | 148 | 509 | $5 \sim 5$ | 531 |
| DECCA | 115 | 4 | 8 | 15 | $10 \%$ | 37 | 308 | $3 ¢ 3$ |
| Alt－statluts | 49 | ${ }^{-}$ | 87 | 15 | 106 | 284 | 233 | 289 |
| DIFF OLEGA | 270 | 0 | 37 | 13 | 198 | 499 | 513 | 519 |
| DIFF LOFAR | 2s0 | 0 | 87 | 18 | 148 | 509 | 523 | 531 |
| jicf mil－3TA | 47 | 0 | 87 | 15 | 108 | crid | 290 | 309 |
| PELA ${ }^{\text {OHEGA }}$ | 53 | $\checkmark$ | 87 | 18 | 110 | 284 | 208 | 343 |
| RELHY LOPFA | 53 | 4 | 37 | 18 | 110 | 289 | 273 | 313 |
| CLASS II 313 |  |  |  |  |  |  |  |  |
| SUFIED PES LOOPS | 14 | 21．4 | o？ | 3728 | 142 | 0110 | 0129 | 6094 |
| PEFLECTIIG SIGNS | －2 | 770 | 67 | 445 | 172 | 1518 | 1528 | 1502 |
| KEFLECTING PMAD | 13 | 24 | b？ | 520 | 522 | 1221 | 1231 | 1205 |
| K－zand POST | 17 | 805 | 67 | 172 | 154 | 1200 | 1249 | 1214 |
| HF，UHF POST | 16 | 83 | 67 | 54 | 115 | 354 | 303 | 338 |
| LF POST | 15 | 438 | 5 ？ | 172 | 154 | 86.3 | 371 | 340 |
| LIGHT／I－R POST | 15 | 359 | 08 | 210 | 194 | 843 | 257 | 832 |
| EURIED MRCNETS | 10 | 219 | 67 | 452 | 189 | 303 | 973 | 647 |
| ULTRHSOHIC FOST | 14 | 595 | 67 | 614 | 173 | 142 | 1487 | 1962 |
| TRAFFIC SEISUR | 15 | 005 | 67 | 29.4 | 191 | 1158 | 1107 | 1142 |
| CLASS III 23 － |  |  |  |  |  |  |  |  |
| MAP－3FET FM PHRSE | 23 | －8 | 127 | 17 | 103 | 322 | 0.7 | 349 |
| HID－EEHJD FII PHASE | ${ }^{\text {cal }}$ | 50 | 127 | 27 | 2u5 | 767 | 733 | 735 |
| PLS．こE T －0－ARRIUAL | 258 | 140 | 327 | 50 | 183 | 957 | $98{ }^{\text {c }}$ | 935 |
| HOISE CORRELATIOH | 79 | za | 327 | 25 | 179 | 654 | 863 | 665 |
| DIRECTIOH FIMDER | 4 | 79 | 67 | 16 | 15 | 331 | 319 | 319 |
| Class I＇ |  |  |  |  |  |  |  |  |
| TRAFFIC LOOPS | צ | 3193 | 67 | 966 | 105 | $4+1{ }^{4}$ | 4424 | ＋42．4 |
| WAISIDE RADIO | 8 | 2766 | 67 | 805 | 276 | 3921 | 3921 | 3921 |
| FHOTOMI－R DETECT | 12 | 1740 | 67 | 413 | 189 | 2－20゙ | 2420 | 2429 |
| ULTRASONIC DETECT | 13 | 1775 | 67 | 412 | 139 | 2455 | 2455 | 2455 |

Table 1－13．Medium City Vehicle Polling


| CLmSS I techiloue | TOTHL fleEt | 5 sic | $\begin{aligned} & \text { SHFLE } \\ & \text { INO } \end{aligned}$ | FFHis | SYte | FESUITMUT vot | PEAT |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| KEYEORPI | 1083 | 537 | 500 | 1983 | 57 | 630 | 116 |
|  |  | 537 | 560 | 148 | 573 | 58 | 1187 |
| STVLUS likp | 1120 | 500 | 5 \％ | 11 br | $\bigcirc 20$ | $t 67$ | 1213 |
|  |  | 568 | 533 | 11 O7 | $\bigcirc$ | 067 | 1213 |
| 2－ACCELEPOHETETS | 108 | 547 | 570 | 1893 | 5 | $\bigcirc 40$ | 1137 |
| L．ficer Melocinit | 1105 | 5 | 579 | 10.3 | 593 | $0{ }^{-15}$ | 1187 |
|  |  | 5 | 57 | 11100 | ${ }^{5} \mathrm{C}$ Of | 6.53 -53 | 1200 12008 |
| LeTRHSUNIC IELO | 1093 | 547 | 570 | 19.93 | 593 | 6.8 | 1187 |
|  |  | $5 \rightarrow \overrightarrow{1}$ | 570 | 14.3 | 593 | $\bigcirc$ | $11{ }^{\prime \prime}$ |
| COSPHCS／ODOHETEF | 1493 | 547 | 570 | 10.33 | 593 | －48 | 11 \＄？ |
|  |  | 547 | 570 | 1693 | $5{ }_{5} 9$ | 6.40 | 118 |
| COOPPRCOLLHEP UEL | 1093 | 547 | 579 | 19 cr | 593 | 0.48 | 1137 |
|  |  | 547 | 570 | 1993 | 59 | 048 | 1187 |
| CRPESTU－SOHIC UEL | 10.33 | 547 | 570 | 19.93 | 593 | 540 | 1137 |
|  |  | 547 | 574 | 19.93 | 5 ग3 | 9 | 1137 |
| OHEGA | 11 〕 | 590 | － 13 | 1137 | $\square^{23}$ | $\underset{5}{ } 27$ | 12 F |
| LOPRN | 1213 | $\bigcirc$ | ［13 | 113 <br> 11 <br> 18 | ${ }_{7}^{6} 89$ | ${ }_{5} 27$ | $12{ }^{12}$ |
|  |  |  | $\bigcirc-0$ | 1153 | 713 | $\bigcirc 6$ | 1367 |
| SECCA | 12 \％ | － 10 | 6 23 | $11{ }^{1}$ | 700 | $\overline{7}$ | $1 \leq 93$ |
|  |  | 000 | $\bigcirc$ | $11-7$ | 709 | 747 | 12.93 |
| fal－staticis | 1480 | $5-8$ | 50 | 1937 | 580 | 027 | 1173 |
|  |  | 5 | 503 | 1037 | 580 | $0{ }^{2}$ | 1173 |
| JIFF OlEOM | 1130 | 540 | $\begin{array}{ll}4 & 13 \\ 0 & 13\end{array}$ | 1127 | $\bigcirc 30$ | 727 | 1273 |
| 3IFF LOFAS | 1213 | O 0 | 5 | 1153 | 6813 | 787 768 | 12 |
|  |  | 607 | 0 3x | 1153 | 713 | 780 | 1347 |
| 3 FFF All－STA | 11 「ご | 587 | －19 | 1133 | ${ }^{6} 73$ | 720 | 12 br |
|  |  | 58 | ${ }^{\circ} 16$ | 1135 | $\bigcirc 73$ | 720 | 12 b |
| Pelat Mmega | 1010 U6 | 50505 | 5058 | $\mathrm{Sidg}_{519} 9$ |  | 108547 | 101093 |
| relaf Lorfit | 4333 | $210 ?$ | ${ }_{21} 10$ | S19 27 | 16053 | 1005 38 80 | 101693 44 |
| CLHSS It |  | 2167 | 2149 | 2713 | 3833 | 38.0 | 4.487 |
| 34PIES PES LOOPS | 10 S7 | 543 | 50 | 10.90 | 537 | 0.3 |  |
|  |  | 543 | 567 | 1890 | 537 | 63 | 1180 |
| KEFLECTING SIGHS | $14 \leq 7$ | 5 ＋3 | 507 | $10 \% 0$ | 537 | － 33 | 1180 |
|  |  | 543 | 50.7 | tuc | 587 | －33 | 1130 |
| feflectitic Pory | $10 \bigcirc 7$ | 543 | 567 | 1680 | 587 | $\bigcirc 3$ | 1139 |
|  |  | $5 \cdot 3$ | 567 | 1898 | $5 \% 7$ | －35 | 11 20 |
| n－3rdj Prist | 10 ك | 549 | 5 5 | 10 27 | 530 | 027 | 1173 |
| HF，iffe Post | 14 br | 5 | 50 | 10.37 | 580 | 6 27 | 1173 |
|  |  | 53 | 547 | 1083 | 5 or | $\bigcirc 13$ | 11108 |
| Lf pust | 1000 | 54 | 50.3 | 1087 | 5 cor | $\bigcirc$ | 1173 |
|  |  | $5 \rightarrow 0$ | 563 | 10 － | 5 \％ | 027 | 1173 |
| LIGIT I－F POST | 1 tb ＞ | 540 | 5 S | 1627 | 5 CO | 027 | 1173 |
|  |  | $5-9$ | 503 | 1987 | 520 | －$\cdot \vec{r}$ | 1173 |
| Suritu hforiets | 103 | 5 43 | 507 | 10.90 | 507 | ${ }_{6}^{6}$ | 11 Ev |
| ULtacohic fat | 10 cos | 5 ， | 563 | iv $3 \overrightarrow{7}$ | 5 cis | $\square 5$ |  |
|  |  | 5 | 503 | 149 | 53 | －${ }^{-1}$ | 1173 |
| tearfic seisup | 1080 | 5 | 503 | 1587 | 530 | 527 | 1173 |
| 12 |  | 54 | 563 | 1937 | 53 | $6{ }^{-}$ | 1173 |

D．Large Model City AVM CostSummary Tables
Table 1－14．Large Model City Parameters Used in AVM Cost Analysis
fipea IS 40 soubfe illes．
LAST HEST IISTAMCE IS 13.9 mLES．
MORTH 3OUTH DISTFHCE IS 27.2 hilles．

TOTAL ROAD HILEAGE IS 7736 hiles．

THE HUHEEF OF IHTER：SECTIOHIS is 35000：

THE ESTIMATED THIIEER OF RGAD SEEMENTS $1 \approx$ 7
THERE RRE 1000 CARS IH THE FLEET
find There rre a hotofcycles．

THE HUHIRER OF UEHICLES DH EACH SHIFT IS：

TIFET FHIFT HAK． 500

FIRST SHIFT HIN． 500

EECOHD SHIFT MHK．500

SECOHI SHIFT HIN． 500

THIRI SHIFT HAX．50日

THIPJ SHIFT HIN． 505

Table 1－14．Large Model City Parameters Used in AVM Cost Analysis（Cont＇d）

## THE CITY WQULD REQUIFE 29 WIDE－BAND OR

## FULEE T－D－A HITTENIA SITES AND 106 NARROW

EAND RNTEHHA SITES WITH 7 GND 3 SIILE COUERAGE RRDII．

Table 1－15．Large Model City AVM CostSummary

| Lhrge hoinl citr CLAOS I |  |  |  |  | 0－11 | totals |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | THOUSPMES OF |  |  |  |  | Toral |  |
| ＇techirgue | CAPS | SITES | BASE | IHST |  | W0L | SYHC | Ramboh |
| KErEJRRD | 135 | 0 | 121 | 45 | 115 | 576 | 410 | 416 |
| STILUS MAP | 2550 | 0 | 121 | 45 | 125 | 3001 | 2841 | 28.1 |
| 2－HCCELEFOKIETERS | 1600 | 0 | 161 | 118 | 200 | 2231 | 2428 | 2378 |
| LFSEP VELOCIHTR | 1730 | 0 | 161 | 145 | 250 | 2496 | 2693 | 2643 |
| LSTRASOHIC VELO | 1270 | $\theta$ | 161 | 110 | 250 | 1951 | 2148 | 2093 |
| COHPASS／ODOHETEF | 1465 | 0 | 161 | 36 | 148 | 1956 | 2196 | 5093 |
| COMPMSS／LASEP UEL | 1855 | 0 | 161 | 160 | 190 | 2526 | 2766 | 2003 |
| CMPSS－U－SOHIC YEL | 1585 | 0 | 151 | 110 | 194 | 2196 | 2435 | 2333 |
| DIECB | 2700 | 0 | 141 | 90 | 175 | 3206 | 3531 | 3469 |
| LGRAM | 2800 | 0 | 141 | y | 175 | 3366 | 3631 | 3539 |
| DECCR | 1150 | 0 | 1－1 | 70 | 175 | 1096 | 1961 | 1411 |
| AII－STATICATS | 408 | 4 | 141 | 60 | 168 | 321 | 1111 | 1904 |
| DIFF．OHEGA | 2709 | 0 | $1+1$ | 90 | 175 | 3200 | 3456 | 346y |
| Miff LOREH | こひい | $\mathfrak{6}$ | 141 | 98 | 175 | 3366 | 3556 | 3589 |
| DIFF $\mathrm{FIM-STA}$ | 465 | O | $1+1$ | 68 | 108 | 485 | 1176 | 1270 |
| RELAY OHEGA | 525 | 6 | 141 | 90 | 200 | 1116 | 956 | 1350 |
| RELAY LORFA | 575 | 8 | 141 | 90 | 200 | 1166 | 1006 | 1400 |
| Clifis II |  |  |  |  |  |  |  |  |
| EURIED RES LOOPS | 140 | 28550 | 121 | 48607 | 115 | 77703 | 77798 | 77543 |
| REFLECTING SICNS | 480 | 7708 | 121 | 4360 | 820 | 13641 | 13736 | 13461 |
| REFLECTINS ROAD | 125 | 8 －8 | 121 | 5110 | 4315 | 10671 | 10760 | 18511 |
| X－BFAD POST | 179 | 8950 | 121 | 1625 | 635 | 19701 | 10856 | 10601 |
| HF，UHF POST | 155 | 575 | 121 | 444 | 242 | 1 9yb | 2091 | 1436 |
| LF POST | 159 | 4375 | 121 | 1630 | 640 | 2076 | 7171 | 6910 |
| LICHT－I－R POST | 1.45 | 3509 | 121 | 2010 | 1890 | 6936 | 7831 | 6776 |
| EUPIED MAGHETS | 109 | 2056 | 121 | 5767 | 109 | 9194 | 9199 | 8944 |
| ULTPASONIC POST | 135 | 5950 | 121 | 6045 | 385 | 13236 | 13331 | 13876 |
| TRFFFIC SENSOR | 145 | 0650 | 181 | č50 | 116 | 10930 | 18131 | Y876 |
|  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| HID－EAND FM PHESE | 2905 | 336 | 202 | 144 | 240 | $3 \% 0$ | 4086 | 4161 |
| PULSE T－0－APRIUAL | 2575 | 1484 | 332 | 423 | 253 | 5119 | 5369 | 5394 |
| NOISE CORRELATIOH | 785 | 39 | 382 | 115 | 202 | to72 | 1762 | 1787 |
| DIPECTION FINDER | 35 | 80 | 151 | 30 | 154 | 569 | 4.49 | 449 |
| CLRSS 10 |  |  |  |  |  |  |  |  |
| TRAFFIC LOOPS | 80 | 68763 | 121 | 9567 | 950 | 74481 | 79.481 | 79.481 |
| HATMSIDE RADIG | 75 | 61233 | 121 | 790 | 1850 | 71249 | 71249 | 71249 |
| PHDTONI－R DETECT | 115 | $41149{ }^{\circ}$ | 121 | 4835 | 990 | 46401 | 46401 | 46481 |
| ULTRASOMIC DETECT | 125 | 41490 | 121 | 4036 | 920 | 46750 | 46756 | 46756 |

Table 1－16．Large City Vehicle Polling
cicle the m seconios to poll hare ario mily units jeflared

\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline CLASS I TECHUIOUE \& TUTHL FCEET \& \& $$
\begin{gathered}
\text { SIHPLE } \\
\text { HOL }
\end{gathered}
$$ \& Fruls \& \＄ill \& CETHISAHT \& T Phitg <br>
\hline \& 168 \& 2 bi \& 5700 \& 1190 \& $\cdots$ \& － \& 12007 <br>
\hline STILS THP \& 112 リ® \& 5s ${ }_{5}^{51}$ \& 50 30 \& 11930 \& $\bigcirc$ \& 506 \& lưu <br>
\hline \& \&  \& 5933 \& Ific ef \& 02 va \& cs 67 \& 12．3 <br>
\hline a－ficceleporieters \& 180 \& 54.87 \& 5000 \& 111 施 \& $5{ }^{4}$ \& 00 mj \&  <br>
\hline LHSER HELOCIHTP \& 110 br \& 54 57 \& 5 \& 11130 \& 34.33 \& ob cy \& $1 \stackrel{\text { cos }}{ }$ <br>
\hline \& 110 br \& 53 \& 50 \& 112
112
10 \& coll 107 \& 0\％${ }_{0}$ \& 124 <br>
\hline ULTPASIOUIC HELO \& 1543s \& 5767 \& 5840 \& 1113 \& $5+33$ \& －8 40 \& 129y 12 <br>
\hline \& \& ET of \& 53 u0 \& 11133 \& 5433 \& 6680 \& $12 \widehat{6}$ <br>
\hline COMPHSSADOHETEP \& 10935 \& 54.87 \& 5300 \& 11133 \& 593 \& ¢ 00 \& 1 c ¢ <br>
\hline COTPROCLHSER IJEL \& \& 5 \& 50 \& 11133 \& 59 \& 065 \& 122 or <br>
\hline \& \& 5， 07 \& 5 \& $\begin{array}{ll}111 \\ 111 & 33 \\ \\ 1\end{array}$ \& 5 \& to 0y \& lie of <br>
\hline CIPSS／U－SOHIC UEL \& 10933 \& 5． 57 \& 50 \& 1113 \& 59 \& 0680 \&  <br>
\hline \& \& $5 \cdot 97$ \& 5009 \& 11133 \& 5932 \& O\％¢0 \& 成 <br>
\hline Ofrcer \& 1150 \& 59 us \& －2 3 \& 115 nt \& 0300 \& ${ }_{4} \mathrm{DF}$ \& $131 \approx$ <br>
\hline LOPrn \& 12133 \& 54 us \& bci ${ }^{3}$ \& 115 bi \& 6309 \& $7{ }^{7}$ \& 131 ぶ <br>
\hline Lornt \& 13 \& 09 51 \& 6460
0409 \& 117
117

178 \& $7!33$
-33 \& －8090 \& 13467 <br>
\hline DECCA \& 12000 \& 50 cos \& 0333 \& 1506 \& 70 0y \& $\bigcirc 567$ \& 135 <br>
\hline HIT－STATIONS \& 16s 00 \& ${ }^{637} 609$ \& －3 3 \& 110 b7 \& 70.00 \& $\bigcirc 0^{\circ}$ \& 123 <br>
\hline \& \& 5.450 \& 53 \& 11 ber \& So nou \& cy 07 \& 12103 <br>
\hline DIFF EMECA \& 11500 \& 59 \& 6233 \& 115 mis \& 66 \&  \& <br>
\hline \& \&  \& Et 0 \& 115 o？ \& 0\％ 0 \& $\bar{T} 47$ \& 131 こ3 <br>
\hline miff Lopalt \& 13133 \& 6467 \& \％4 6 \& 1173 \& $71 \%$ \& 7840 \& 104 <br>
\hline DIFF RH－STA \& 11733 \& 69
53
50 \& 吹 8 明 \& 1173 \& 7133 \& 7840 \& 13.07 <br>
\hline \& \& 50 \％ \& －2 90 \& 115 \& ${ }_{67}{ }_{6}{ }^{3}$ \& 7\％ \& $130{ }^{130}$ <br>
\hline PELHY OHEGA \& 1410400 \& 5056100 \& 5653 33 \& 510607 \& 1 4650 \& 100565 \& 10113 <br>
\hline \& \& 5 S 90 u \& H453 33 \& 51ko o？ \& ivi ${ }^{0}$ \& 1095667 \& 10113 <br>
\hline RELA，LOPAM \& 43333 \& 2lo e？ \& 22000 \& 27\％ 33 \& $\cdots 3$ \& 369 40 \& ＋46 of <br>

\hline | CLROS It |
| :--- |
| EUPIED FES LOOPS | \& 1113 \& 21067

5507 \& 22000
5900 \& ごら 33
11233 \& $\approx 3$ \& 390 dos \& 4 Ab 67 <br>
\hline \& \& 5567 \& $5{ }^{\circ} 98$ \& 11233 \& mi 3 \& OS 4 \& 124 120 <br>
\hline REFLECTIHESTEAS \& 11133 \& 5567 \& 5904 \& 11233 \& 0133 \& 0300 \& 12467 <br>
\hline FEFLECTIUG FOAD \& 11133 \& bit ${ }^{51}$ \& 5900 \& 1123 \& 01 \& 1300 \& 12， 47 <br>
\hline \& \& 55 br \& －5960 \& 1123 \&  \& 6e 010 \& 154 <br>
\hline －EAMI POST \& 110 67 \& 55.3 \& 58 of \& 1106 \& $00^{0} \mathrm{O}$ \& ${ }_{6} 73$ \& 124 <br>
\hline HF，UHF POST \& 33 \& 55.33 \& 53 \& 11280 \& 50 67 \& D7 33 \& 124 u6 <br>
\hline \& \& S4 57 \& 50 \& 11133 \& 或30030 \& －0 0 \& 102 bi <br>
\hline LF PUST \& 110 b \& 550 \& $5{ }_{5} \mathrm{O}_{7}$ \& 11240 \& $0{ }^{5}$ \& $67 \approx$ \& $12, ~ \cup 19$ <br>
\hline \& \& G53 \& 5305 \& 112 \％o \& 06）of \& 6.73 \& 12.40 <br>
\hline LIGHT／i－R PUST \& 110 bT \& 5533 \& 5307 \& 11299 \& of of \& 07 33 \& 12.46 <br>
\hline E1dPIEJ difutiets \& 11153 \& 55.35 \& 55 \& 11208 \& my 67 \& 6735 \& 52400 <br>
\hline \& \& 35 67 \& 5900 \& 1123 \& 6153
015 \& 60 und \& 124 of <br>
\hline ULTPASOHIC POST \& 110 6 $\overline{7}$ \& 5533 \& 5867 \& 1120 \& 508 \& ${ }_{0} 9$ \& 12－6\％ <br>
\hline TPRFFIC SEHSOR \& \& 55.3 \& 56 \& 11200 \& ro e7 \& いT 3 \& 124 <br>
\hline TFAFFIC SELISGR \& 110 er \& 55 \& 5867 \& 11200 \& 5067 \& $67 \approx$ \& 12409 <br>
\hline 13 \& \& \& \& 1200 \& 69 \& $\bigcirc$ \& に\％ 51 <br>
\hline
\end{tabular}

## IV. AVM SYSTEM ACCURACIES AND COST BENEFITS

## A. System Parameters ThatAffect AVM Costs

The prediction of the expected accuracies of AVM systems is essentially a probabilıstic problem. Actually there are two distinct problems, one a precursor to the other, depending on the class of AVM system. Classes I and III are loosely referred to as "random route" systems because the techniques have the capability of vehicle location anywhere within their surveillance areas. Classes II and IV are called "fixed route" systems because the location capability exists only in the vicinities of signposts that are distributed along the wayside or on the roadway at intersections within the covered area. Besides the inherent range of uncertainty in the location measurements provided by individual AVM techniques, Classes I and III are subject to another location error, which is the shift in the moving vehicle's position during the interval between the instant of polling and the display of location data at the base. On the other hand, Class II and IV techniques provide location information only at the time when the vehicle passes within the sensing radius of a wayside or buried signpost. This information is the best available until the time that the vehicle enters the sensing radius of another signpost. A measure of this uncertainty in location is required to determine the "inherent" accuracy of the signpost AVM techniques. This is particularly true when the signposts are less than maximally dense; that is, when the signposts are placed two or more intersections apart.

It is intuitively reasoned that if the signpost sensors in Classes II and IV are placed at each intersection, then the location of any vehicle can be found to plus-or-mmus one block. It also follows that if the sensors are placed in a diamond pattern at every other block in each direction, then the accuracy is plus-or-minus two blocks. This reasoning is valid only $f$ every passage through instrumented intersections by all vehicles is known. If the polling technique or RF channel loading is such that this data frequency cannot be assured, then the achievable accuracy is not as well known. A tutorial treatment of the less dense signpost placement by Markov, or randomwalk, processes is included in Part Three of this Report. The analysis technique leads to a prediction of the mean and variance of the distance traveled by a vehicle starting at an unsensed intersection before it passes a sensed intersection. The results of this technique for various signpost densities are as follows:

| Ratio <br> (Sensed/Unsensed) | Mean | Varıance |
| :---: | :--- | :--- |
| $1 / 1$ | 1 | 1 |
| $3 / 8$ | 1.778 | 1.778 |
| $3 / 9$ | 2 | 2 |

The second approach to the system accuracy prediction considers not only the wherent error in the vehicle location technique but also the additional inaccuracies introduced by the delays in
successive pollings of the vehicles and by the computation of location when the vehicles in the fleet are moving at various speeds. In Part Three of this Report, the analysis, the method of solution, and the tabular results are presented.

The technıque for predicting the location accuracy was used to generate the family of curves in Fig. 1-36. These contours of system accuracy correlate the independent variables of the polling interval and the standard deviation of the inherent error. The accuracy contour yields the $95 \%$ confidence interval for vehicle fleets that move with an exponential velocity distribution such that more than half the vehicles are moving at speeds less than $15 \mathrm{mph}(6.67 \mathrm{~m} / \mathrm{s})$. It can be seen from the curves that either the polling interval or the inherent error can quickly dominate the achievable system accuracy if ether is very large. The curves are shown for the system accuracy interval of 100 to 1000 meters ( 0.1 to 0.6 mlle ). The curves for less than 100 and greater than 1000 meters are repetitions of those shown and can be derived with subtraction or addution of a unit constant on both axes (equivalent to division or multiplication of the interval or deviation by a factor of 10).

## B. Estimated Cost Savings Based on Urban Parameters

1. System accuracy estimation. The accuracy to be expected from any given AVM system in a locality $1 s$ estmated by a step-by-step process. First, from the data provided for the particular city, the maximum and minimum number of vehicles deployed is obtaned. Next, the number of bits in the location message required from each vehicle for each technique is determmed. The time required to poll the deployed vehzcles with a $0.1-\mathrm{sec}$ radio turn-on time is then computed for the redundant mode of the random polling process. This value yields very conservative (or pessmistic) polling mtervals for the two values of vehicles deployed. These intervals together with the value obtained from the table of technique accuracies provide the entries to the graph of system accuracies. These curves are prestored in the computer program. A rather simple linear interpolation program yields a maxımum and munimum estimation of the $95 \%$ confidence level of system accuracy for the maximum and minmum vehicle deployments. The location accuracies used are usually greater than the standard deviation value.
2. Vehicles saved estimation. Based on the prior work of Larson (Ref. 2), Knickel (Ref. 3), and Doering (Ref. 4), a quantitative measure of efficiency increase in responding to calls for service should be determinable from the accuracy of the AVM system. One of the approaches to this problem is to compare a situation where, in response to a call for service, the dispatcher always sends the vehicle responsible for a beat to that where the location of the vehicles is known and the "closest" vehicle is dispatched to the scene.

The efficiency comparison is made either in the excess time required or the excess distance travelled by the beat vehicles relative to the closest located vehicles. The conclusions of this approach are generally that a vehicle location accuracy of about $1 / 5$ the beat-side dimension is


LOG $_{10}$ STANDARD DEVIATION OF INHERENT ERROR

Fig. 1-36. Vehicle Polling Intervals vs $95 \%$ AVM System Accuracy
sufficient. Additionally the service improvement is found to be about $7 \%$ for the locator system dispatches versus the "center of mass" or beat vehıcle dispatches.

The more recent study of Doering (Ref. 4), however, compares response time performance in a situation with differing absolute accuracy values of the AVM system and a given fleet size with the number of vehzcles required to provide the same response time with no AVM. Doering's study ind ${ }_{1}$. cated that, in the area studued (the city of Orlando, Florida), 34 vehicles in the AVM fleet where the accuracy is 240 meters ( 800 ft ) would provide a response time which would require 35.8 vehicles in a non-AVM fleet. Extrapolation of the curves presented by Doering indicates that 8 to $10 \%$ fewer vehicles in an AVM system fleet with perfect ( 0 feet) accuracy can provide the same response performance as the larger number of vehicles in a non-AVM fleet. Extrapolation in the direction of less accurately known location, indicates that there is little improvement in response tume with location accuracies of 450 meters ( 1500 ft ) or more. It may be coincidental that this value is about 0.3 km ( 0.2 mile), which is $1 / 5$ the average beat side dimension in the Orlando simulation studies. A plot of the increase required in a nonAVM vehicle fleet to equal AVM vehicles response time performance versus accuracy shows a linearly decreasing value as the AVM accuracy decreases.

For the purposes of this study, a $7 \%$ increase in efficiency is assumed for a perfect AVM system, with the percentage decreasing linearly to zero at an AVM accuracy of 0.2 times the average beat side length. The average beat is calculated by dividing the area by the number of vehicles deployed.

For maximum and minımum deployments, the efficiency uncrease assumption yields dufferent values for the same AVM technique accuracy. In cases where the minimum deployment is substantially lower than the maximum, the apparent beat size may be increased to the point where an AVM technique which yrelds no efficiency increase with maximum deployment may display a marked improvement in response. Addationally, the minmum deployment decreases the polling time interval which provides an additional improvement in system accuracy.

The calculation of cars saved is based on a reasonable reciprocity assumption that fewer cars with AVM can yield the same performance as that obtained now with a given fleet size The number of cars saved is determined by multiplying the percentage efficiency value, obtained from the beat dimension and system accuracy, by the number of vehicles deployed. Savings of less than one vehicle are allowed by the calculation. As stated before, the factors tending to increase efficiency are such that, in some cases, the number of cars
saved with minumum deployment exceeds that for maximum deployment with a given technıque.
3. Estimated 5-year cost saving. The 5-year saving calculation, presented in Tables 1-17 through 1-20 is an attempt to place a dollar value on the efficiency increase which might in turn indicate possible choices of candidate AVM systems. The calculation assumes that each car saved is worth $\$ 150,000$ annually, which is primarily salaries and overhead (as of 1974). This is an average value for a 1 -man car based on 5 salaries and $100 \%$ overhead. The saving for small, medium, and large cities is a straightforward multiplication of the maximum of the cars saved times the annual value of the car munus the $O-M$ costs of the AVM technique. The value

Table 1-17. Small Model City Cost Benefits from AVM System Usage


Table 1-18. Medium Model City Cost Benefits from AVM System Usage

obtained is then multiplied by 5 years for the total saving.

The 5-year saving is positive only $f f$ the value of the car saving exceeds the annual $O-M$ cost. The calculation is performed for a given technique only $f$ a car saving is indicated, and the result 15 presented regardless of sign. No calculation is performed if no car saving is indicated.

A simple summation of savings rather than a present worth of an anuity calculation is justified on the basis that it is less speculative and might be more nearly correct falaries rise at a percentage rate which exceeds the rate of return that can be realized on 5 -year municipal investments. The 5 -year saving estimation is presented solely for AVM system comparison purposes.

## Table 1-19. Large Model City Cost Benefats from AVM Systems Using One RF Channel




Table l-20. Large Model City Cost Benefits from AVM Systems Using Two RF Channels


## V. COMPUTER PROGRANS FOR ANALYSES OF AVM NEEDS

The cost estimates for the AVM techniques are in almost all cases precisely that - estimates as of 1974. They have the additional shortcoming that large-scale production is assumed, which accounts for the gene rally low system cost amounts Therefore, additional studies are necessary to refine these estimates in view of the rapidly changing technology and costs.

Although the cost estimation procedure for AVM systems in model cities is a valid technique, it does not take into account the individual differences of real cities. That is, the system engineering aspect where the vagaries of a particular coty and operational methodology are considered has not been included. The AVM system cost estimation and particularly the performance estimation and resultant estimated savings are essentially averaging processes. Since each city differs in details from each other city, and the AVM system cost, performance, and impact depend on these differences, final selection of an AVM system will require an ind ovidual analysis such as those presented in Part Two.

An individualized analysis for a particular city requires the two following steps. (1) Synthesis of AVM systems corresponding to each of the desired concepts as they would be configured for the physical, political, and cost environment of that city, and (2) evaluation of the effects of each of those systems. The process of synthesizing a particular AVM system is a straightforward but tedious task, requiring detailed technical knowledge that may not be readıly avaılable in real cities. It can be made easuly available, however, by the development of an AVM system synthesis computer program, as is described later. The expected effects can then be assessed by using the resultant systems in a system sumulation computer program, which is described in more detail in Section B. Since these two programs were planned to be developed in Phase One of this AVM Systems Study project, they do not yet exist.

## A. AVM System Synthesıs Computer Program

The synthesis program will be based on design algorithms, equations, cost estimates, and the AVM data base developed in Phase Zero of this Study. These program components include antenna siting algorithms for time-of-arrival systems, message length equations for different location technique and polling combinations, accuracy estimation equations for various reporting intervals or signpost densities, and lufe-cost equations. A prelimlnary concept of the basic elements of the AVM system synthesis computer programis shown in Figure 1-37. A concept of the operations sequence in using the synthesis program is presented in Table 1-21. Salient features of the synthesis program are listed in the following subsections.

## 1. City and fleet data for AVM System

 Synthesis Program. The synthesis program will first summarize the data provided from the input file. The purpose of this step is to provide the user wath an opportunity to review the input before actually running the synthesis program. Table 1-22 lists some of the parameters that will be included in the data input summary.Table 1-21. Operating Sequence of
AVM System Synthesis
Computer Program
Step 1. The user whll supply the values of those parameters that descrube his partıcular city. Some of the data may be farrly extensive, for example, geocoding data or DIM $E$ file type information which describes the city street/block system in detall. For information of this type a computer-readable data fule will be used. An auxiliary program, separate from the AVM system synthesis program, will be developed to facilitate the interactive development of the data file.

Step 2. The synthesis program will read the datafile and determıne the AVM system configurations suited to the city. If any data $1 s$ missing or incomplete, the program will undicate which systems cannot be evaluated and provide an opportunity to modify the data file.

Step 3. The program will present basic comparison data for each system confıguration option.

Step 4. After selecting the vable confıguration options, the program will shift to a "trade-off" or compromise mode in which the user can access further detail and investigate the options avaulable withon a particular choice of system concept.

Table 1-22. City and Fleet Input Data for AVM System Synthesis Program

City name AAAAAAAAAAAAAAAAAAAAAAAA Area monitored. XX.X sq miles
Maximum $X$ and $Y$ dimensions: $X X . X X \mathrm{ml}$, by XX. XX miles

Street length XXX.X miles
Number of intersections: NNNN
Number of road segments; NNNN
Number of vehicles instrumented: NNNN
Average number of vehicles each shift: NN, NN, NN
Number of beats per shift: NN, NN, NN
Shuft hours: HH-HH, HH-HH, HH-HH
Number of dispatcher consoles: $N$
Utilization factor by shift: FF\%, FF\%, FF\% (This $1 s$ the fraction of time available to respond to calls for service).
Average call for service time by shift: HH, HH , HH
RF channel utilization factor: $\mathrm{P} \%, \mathrm{P} \%, \mathrm{P} \%$
RF channel assigned. $N$ Planned: N
LORAN coverage in area?: $\mathrm{Y}-\mathrm{N}$; DECCA? : $\mathrm{Y}-\mathrm{N}$
AM stations in area $\mathrm{K}--, \mathrm{W}-\mathrm{-}, \mathrm{~K}-\mathrm{-}, \mathrm{~W}-$ -
2. AVM Configuration options for AVM Sys tem Synthesis. Each of the AVM options identif 1 ed by the selection process will be described briefly in narrative form. Each will be tagged with an udentity code for later use. Then for each of the applicable options, the following gross data will be presented for comparison:
a. Cost estimates. Total system cost, "present value. "\$XX XXX XXX (These figures


Figure 1.37. Concept for AVM System Synthesis Computer Program
will be for comparison purposes only. A breakdown follows:)

| One-time costs | \$XX XXX XXX |
| :---: | :---: |
| (development, conversion, facilities) |  |
| Installation costs | \$XX XXX XXX |
| Recurring costs | \$XXX XXX per year |
| (operations, maintenance, training) |  |
| Replacement | \$XXX XXX per year |
| (equivalent annual payment at 10\% year) |  |
| Upgrading costs |  |
| Display consoles <br> \$XXX XXX plus \$XX XXX per year (each) |  |
| Fixed sites <br> \$XXX XXX plus \$XX XXX per year (each) |  |
| Signposts <br> \$ XXX plus \$ <br> Vehicle equipment |  |
|  |  |
| \$ X XXX plus \$ | XXX per year (each) |
| Telephone mileage\$XXX XXX plus \$XXX XXX per year (each) |  |

b. Resource utilization estimate.

Radio channels required: XX.X
Microwave or dedicated telephone lines needed: XXX

Computer memory estimate: XXX XXX bytes
c. Performance estimates.

Median location accuracy. XX ft (effective polling rate $=X X$ vehicles/ second)

Fraction of fleet with error
less than $\qquad$ ft: XX\%
less than $\qquad$ $\mathrm{ft}: \mathrm{XX} \%$
less than $\qquad$ ft: XX\%
d. Comments. Design features and other relevant considerations will be noted. Typical comments that mıght apply to specific systems are as follows:
"Vehıcle status is monitored".
"Field unit alarm capability is present".
"Pollmg procedures are inflexible".
"Shared usage by several agencies would be difficult to mplement".
"Effect of weather on performance expected to be smali'".
"Fleet locations easily monitored by public".
"Each 90 vehicles monitored requires an additional radio channel".
"Sensors may require protection from vandalısm".
e. Trade-off potential. This portion of the output will identify significant trade-off possibilities and the potential outcome that could result from those trade-offs. The trade-off relationships will be accessible during Step 4 (Table 1-21) of the program. Typical trade-offs that might be possible for all or some of the systems are these:

Location accuracy vs number of radio channels (via the polling option and rate).

Computing at the command center vs computing on-board the vehicles. (This affects the costs and accuracy vs radio spectrum trade-off.)

Display characteristics vs cost. (These trade-offs may be independent of the other descriptors of the system.)

Location accuracy vs cost (via the spatial density of signposts, the number of fixed sites, etc).
f. Cost benefit estımate, A preliminary estımate of efficiency increase with AVM will also be an output. The cost benefit estimate will be derived from the estimated increase in efficiency and data such as that listed below.

Patrolman average salary:
$\$ X X$, XXX per year
Patrolmen required for each vehicle. N
Support personnel for each vehicle: N.N
Overhead on salaries: PP\%
Repla cement cost of vehicle: \$X, XXX
Mantenance cost of vehicle:
\$X, XXX per year
'Based on the size of the fleet and these parameters, a cost benefit (deficit) first estmate will be provided such as:

> Number of vehıcles saved by shıft. $\mathrm{X}, \mathrm{X}, \mathrm{X}$
> Vehicle cost saving equivalent: \$XXX, XXX AVM capital investment equivalent,
> 10 yr: $\$ \mathrm{XXX}, \mathrm{XXX}$
> 5 yr: $\$ \mathrm{XXX}, \mathrm{XXX}$

The information provided by the AVM system synthesis program will not in itself provide sufficient justification for selection but will be a very important first step that eliminates obvious non-competitive technıques and allows for more detailed consideration of the viable techniques.
B. AVM System Simulation Computer Program

Much work has already been done by others in regard to AVM simulation (see Bibliography). The intent of this study effort $1 s$ to utilize as much of that work as possible.

There is one aspect of the prior work where it is believed-that improvement is needed. This is in the area of AVM system accuracy estimation. Prior AVM simulation work has investigated the overall command and control function to determine the effect of AVM system accuracy on "wrong dispatches" and the average distance travelled as a result of these "wrong dispatches." A "wrong dispatch" results when the closest available vehicle is not the one directed to respond to the call for service. This incorrect action results from not knowing precisely the vehicle locations, and thus the enture system performance is degraded owing to unnecessary distance travelled and time consumed in responding to calls for service.

In these prior simulations of the command and control functions, the investigators assigned values such as a 95 percentule value of a radial error of X feet to the AVM system accuracy. It has been assumed that this error distribution is normal and constant with time. The computer simulation programs determine the exact location of each vehicle from a mobility routine or driver scenario. Then, in order to test the system response to a call for service, each of the exact locations is corrupted in some random fashion with ether $X$ and $Y$ or with an angle and range to the exact location. The apparent location is then used by the dispatching routme in the search for the vehicle closest to the call for service. The foregoing mode of simulation effectively assumes a constant value for the AVM system accuracy which may be misleading for all but those techniques that use very short untervals between vehicle location determinations. Short interval inter rogation of location is not a requisite mode of operation in many AVM techniques and is impractical or mappropriate in others.

A more realistic approach to AVM accuracy simulation 1 s to model the actual vehicle location process, including the expected or appropriate polling technıque and taking into consideration the time lapse from the last location determınation, the motion of the vehicles, and the resultant effect on closest car determination. In this mode of sumulation, the vehicle mobility or driver location routine can be altered by a time-varying location uncertainty, if that is appropriate for the particular AVM system concept. The exact nature of this uncertainty or modification to the exact location may also be a function of other factors in addition to time. These factors may be vehicle speed, physical location at time of interrogation, distance travelled since last location, or distance travelled since last signpost proximity update. These factors will be explicitly considered by the AVM simulation program.

An accurate measure of the reduction in response time requires that a reasonably accurate geocoded definition of the coverage area be a part of the simulation program. Simulations that sum the absolute values of the drfferences in $X$ - and $Y$-distances from the vehicle position
to the location of the call for assistance give a correct solution only for rdealized rectangular cities. Geocoded descriptions of the coverage area will allow an accurate measure of distance in each instance, since the optimum trevel routes can be used in the simulation.

The advantage of using the more accurate AVM simulation models is that a more realistic apprasal of the expected increase in efficiency can be determined. In addition, the possible variations in system configuration that affect performance parameters of the enture system can be investigated with the assurance that the influence of the variation has been considered.

Other technıcal performance parameters that will be considered in the simulation program include the data links involved in the vehicle location process and the effects of errors in reception; the effects of entry of new vehicles into the coverage area, and the re-establishment of the position of "lost" vehicles in relative location techniques. In addition, the actual location algorithm for each technique can be exercised with the expected input data. The preliminary concept of the main components of the AVM system simulation program are shown in Fig. 1-38. As already mdicated, the intent 15 to develop this program around prior work insofar as possible.

Heretofore, simulation has been used almost exclusively in regard to reducing response time. The proposed simulation program will allow the investigation of other aspects of vehicle location. The utility of post data analysis can be evaluated, and the effects of an officer-needs-assistance incident can be assessed, both for the impact on subsequent calls for service and on the response time improvement to the officer in trouble.

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# PART TWO: <br> AVM DATA FOR USER GROUP ADVISORY COMMITTEE CITIES 

G.R. Hansen

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## PART TWO. AVM DATA FOR USER GROUP ADVISORY COMMITTEE CITIES

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## I. COST BENEFITS OF AVM SYSTEMS FOR SEVEN CITIES

## A. Rationale for Selectıon of UGAC C1ties

In order that a more realistic appraisal of the costs and expected performance of AVM Systems could be estimated, police department representatives from several citues were invited to participate in a User Group Advisory Committee (UGAC) devoted to studying AVM technologies. A set of nine criteria was established for selecting typical Southern Californa cities for the UGAC study. Some criteria are obvious and were established for time and economic considerations, while others were arrived at by heurastic processes. In this listing, the future tense is used because the criteria were established before caty selection began. A brief rationale is presented with each criterion, to wit:
(1) City Size. Cities in three categories, (a) less than 20 sq miles, (b) between 20 and 100 sq miles, and (c) greater than 100 sq miles, will be solicited to determine the impact on urban areas to be covered by AVM Systems.
(2) Geography/Topography. Essentially flat as well as hilly areas in the communities are desurable to ascertain the effects on AVM methods as well as the communication data links.
(3) Population Density/Land Use. These criteria are closely allied, and agricultural areas, industrial centers, and suburban as well as high-rise residential areas should be a part of the caties. This criterion will eliminate those cities formed to be wholly agricultural or industrial areas for tax purposes.
(4) Buılding Sizes. The inclusion of high-rise dense metropolatan, low-rise busmess (less than 6-10 stories), mixed business and residential, and suburban areas is desirable to match and extend prior AVM work and to include the effects of these structure distributions on the communication links.
(5) Population. Cities with populations of (a) more than $1,000,000$, (b) between 200,000 and 1,000,000, and (c) less than 200, 000 will be solicited. These numbers are arbitraxy and are not firm, but the population somewhat determines the size of the municipal government. It is felt that this criterion is desirable as differing governing bodies will require AVM information to different degrees. Additionally, the participants in the user group whll probably have different authority wathin their caty governments as a function of population. It is belreved, that those from smaller cities may be closer to the policy making level than those from major cxties.
(6) Willingness to Cooperate. This is an obvious but important criterion and is
difficult to assess beforehand. Itis essential because the participants will be required to furnish data about their city as well as being regular in meeting attendance.
(7) Pursuing or Contemplating AVM. This criterion is necessary to assure some active interest in the study effort.
(8) Close to JPL. Economic considerations require this criterion since expense monies are not avallable in the grant for the participants. Additionally, regular frequent meetings are required and extensive travel time would be an additional expense to the participating city.
(9) Must Have Public Safety Department. This is an obvious and perhaps trivial requarement, but is necessary to eliminate those cities that contract for police services with another government agency. These cities would probably faxl Criterion (7) as well. This criterion is a natural outgrowth of the principal thrust of the proposed work whach will focus on public safety vehicle location.

None of the foregoing criteria were intended to preclude partxcipation by governmental bodies other than cities, such as countres. By criterion (8), only Los Angeles and possıbly, San Bernardino, Ventura and Riverside counties could have been considered.

Seven cities were selected which met the majority of the criteria. Small cities were Montclair and Monterey Park. Medxum cities selected were Pasadena, Long Beach, and Anaherm. The large cities were San Diego and Los Angeles.

Senior police officers from each of these cities participated in the UGAC and provided information concerning police operations and plans as well as statistical data for the individual cities.

## B. Parameters Used in AVM Cost Analyses

Each UGAC city had different modes of operation and requirements regarding the implementation of AVM systems. For example, some police departments operate on a three-shift basis, while others use the ten-four plan where the offacers work four 10 -hour days in sequence. In responding to calls for service, some police departments use only patrolling vehicles while others dispatch the plain colored (1. e., pastels) in response to citizen calls. The inclusion of motorcycles, exther two- or three-wheelers, in the AVM system was planned by some cities, but not by others. In the main, however, there is sufficient commonality of parameters to allow for automation of the AVM cost and performance estimation procedures.

1. Number of vehrcles in the fleet. The total number of vehicles to be instrumented is the basis for the car cost estumates. Motorcycles were not included because a satisfactory digital message capability for motorcycles does not yet
exist. Vehicles, which in general do not respond to calls for service were also not included. The maximum and minimum number of vehicles by shift was determined and normalized to a three. shaft operation. This parameter is necessary to determine vehıcle polling intervals.
2. City area, street mileage, number of intersections and road segments. This information was provided by the representatives for the UGAC cities. The beat area is an important parameter which is used in the AVM system accuracy estimation, but no standard or common method of determining this parameter could be found. In some cities, the beats are correlated with the crime reporting technique. In others, the beats are periodically readjusted as determined by the average number of vehicles deployed on particular shifts. The beat size parameter is an independent variable in predicting the responsetime improvement that should accrue with a given location accuracy value. For the purposes of this study, the beat size was placed at the values resulting from dividing the city area by the number of vehicles deployed. This average value assumption cannot be wholly justified when, for example, beats vary from 6 blocks to 49 square miles in size as they do in San Diego.
3. Number of signposts or fixed sites required. The fixed site enumeration parameter in Class II and IV AVM systems was determined from the data supplied concerning the number of intersections or road segments. Where the tech. nique was dependent on the number of lanes in the segment, the average value of 2.4 lanes per street segment was assumed as in the model cities. For the Class III AVM techniques, the placement and/ or the number of widely distributed fixed sites required was determined by an algorithm which was only a function of the area in the model city estimations. The boundaries and shape of the UGAC cities seemed to dictate a more realistic approach. Boundary outline maps of each city were prepared, and the most optimum placement of a grid representing the spacings for narrowband and wide-band antennas was determined. The minimum number of sites that would be necessary was thereby determined. The assumptions made were that there were no "difficult" RF areas that would require additional coverage, and that a fixed site could be placed where needed regardless of zoning, existing structure, or geographical restrictions.
4. Costing procedure for AVM Systems in UGAC cities. The costing of the various AVM system configurations for the UGAC cxites was accomplished through the use of the APL computer programming language (see Part Three). The costs of vehicle equipment, fixed sites, base equipments, and polling elements were stored in the table form by technique and cost category (e.g., equipment, installation, operation and maintenance). This assemblage forms the cost data base. The various parameters for each UGAC city are also stored in a prescribed manner as follows:
(1) Urban area in square miles.
(2) East to West extent in miles.
(3) North to South extent in miles.
(4) Road mileage.
(5) Number of intersections.
(6) Number of road segments.
(7) Number of vehicles in AVM fleet.
(8) Number of motorcycles.
(9) Maximum number vehicles deployed in first shift.
(10) Minimum number of vehicles deployed in first shift.
(11) Maximum number of vehicles deployed in second shift.
(12) Minimum number of vehicles deployed in second shift.
(13) Maximum number of vehicles deployed in third shift.
(14) Minımum number of vehicles deployed in third shift.
(15) Number of dispatcher consoles.
(16) Number of small coverage (or narrow band) Class III AVM sites.
(17) Number of wide coverage (wide-band) Class III AVM sites.

The cost estimates (as of 1974) are compuled into the cost categories after multiplying by the appropriate parameter. The program is very simple, being really a programmed desk calculator with automatic input. The rationale for programming was to avoid a repititious procedure of calculating fine cost categories and obtaining three totals for each of 36 AVM techniques in the seven UGAC and three model cities and to simplify future cost estımations.

## C. Descriptions and Summary Analyses of UGAC Cities

In Sections II through VIII, outline maps of each UGAC city are presented along with detanled listing of each city's physical parameters, AVM cost summaries, vehicle polling cycle times, and estimates of the AVM system accuracies and 5-year cost savings. The seven selected caties were Anaheim, Long Beach, Montclair, Monterey Park, Pasadena, San Diego, and Los Angeles. Thirty-six techniques in the four AVM classes were investigated for each city. Each of the seven cities was treated as an entity, with the exception of Los Angeles which was evaluated for each of its four geographical bureaus. Additionally, because of the large number of vehicles deployed in the cities of San Diego and the four Los Angeles bureaus, the system accuracues were determined for shorter cycle times or polling antervals. That is, more than one RF channel (half-duplex) was allowed for these areas.

In this Section, the summary analyses for each UGAC caty are based solely on a comparison of the estimated 5-year saving and the estimated costs (as of 1974) of particular AVM systems.

The 5 -year saving is predicted on only one factor of AVM performance, namely response time improvement. There are many other aspects of AVM systems which should enter into the decision process. Many of the thirty-six listed techniques which appear viable have never been developed or tested in typical urban environments. Therefore, only the developed and/or tested concepts will be discussed in the following summary descriptions. Complete tabulations are given in Sects. II to VIII.

1. Anaheim, CA. This city might be characterized as a break-even city with response time improvement such that cost savings just equal AVM costs, but only for the dead-reckoning techniques in Class I. Anaheim is slightly smaller than the medium model city (see Part One, Sect. III) in both area and fleet size, and the cost summary indicates Class I system costs for the dead-reckoning techniques of about $\$ 280,000$. The 5-year saving is about $\$ 300,000$ for a magneticcompass/odometer system with a system accuracy of 50 to 75 meters.

The Class II AVM systems which indicate some car saving are the wide-spaced signposts and buried magnets. The accuracies achievable are roughly 250 meters and 50 to 75 meters, respectively. The cost of the Class II wide-spaced signposts is about twice the saving, while the buried magnets may cost four times the 5 -year saving.

The most accurate Class III and all Class IV systems resulted in car saving, but the cost saving was negative. (See Sect. II.)
2. Long Beach, CA. The same AVM techniques as in Anaherm are viable in this city, but because the city is slightly larger in area with a substantially bigger vehicle fleet, the costs are about $\$ 50,000$ more for the Class I deadreckoning techniques. The 5 -year savings are lower, about $\$ 160,000$, because the maximum deployment considered is less than in Anaheim.

There is a large difference between Anaheim and Long Beach in the Class II AVM systems as Long Beach has almost four times the road mileage and almost twice the number of intersections. Long Beach is unique in having a large number of named dedicated alleys in the central area which results in an intersection density of $144 / \mathrm{km}^{2}$ ( 400 per square mile). This factor causes the Class II and Class IV techniques to have a greater number of installations than are really required. Widespaced signposts and buried magnets indicate car savings, but the 5-year figure is well below the systems cost. If the high central density were reduced to a more reasonable value, the disparity between cost and saving would lessen to the point where the saving would be half the cost.

The pulse TOA Class III technique and all the Class IV systems indicated car savings, but cost savings were negative. (See Sect. III.)
3. Montclair, CA. In this city, the deadreckoning techniques of Class I AVM and most of the techniques in the other classes indicate car savings primarily because system accuracies are very high. This is a direct result of a very short polling cycle time. The 5 -year savings for all systems that indicate a saving are negative and exceed a "loss" of $\$ 200,000$. The car savings are
in the order of $5 \%$ of the deployed vehicles (4 to 7), that is, 0.2 to 0.4 cars.

Despite the fact that Montclair has a widespaced sagnpost AVM system installed and operational for over a year, this analysis indicates that the cost is substantially greater than the saving. The reason this analysis is faulty in this case is that Montclair does not have either a computer in the system nor the operation and maintenance ( $\mathrm{O}-\mathrm{M}$ ) personnel indicated as required for all systems.

The system accuracy indicated for the widespaced Class II signposts is about 250 meters, which is quite close to that achieved in Montclair. The installed system has an accuracy of 0.2 km ( $1 / 8 \mathrm{mile}$ ) with slightly fewer signposts. The system costs are quite similar for the technique if the $0-\mathrm{M}$ category is omitted ( $\$ 60 \mathrm{~K}$ versus $\$ 71 \mathrm{~K}$ ). (See Sect. IV.)
4. Monterey Park, CA. Car savings are indicated for all classes of AVM in this city. Again as in the other small city, or small model, the cost saving is near zero or negative. This caty, because of the great difference between maximum and minimum deployment and short polling cycle shows a greater car saving when fewer vehicles are deployed. If the $O-M$ costs were greatly reduced, the 5-year saving would exceed the costs. (See Sect. V.)
5. Pasadena, CA. This city 15 roughly half-way between the small and medium models. Again a car saving $1 s$ shown in all AVM classes with negative 5 -year cost savings. Again, the short polling cycle causes little degradation of achievable accuracy. The O-M costs are the principal element mitigating aganst a positive saving, and the value for cars saved is less than a whole car. (See Sect. VI.)
6. San Diego, CA. In this city, vartually every AVM technique indicates a positive 5-year saving.-The Class I dead-reckoning techniques system costs are exceeded by the estimated savings, and the Class III costs are close to the savings. This result occurs despate the poor system accuracies caused by relatively long polling cycles. There is a substantial car savings because the averaging of beat areas leads to results in which apparent response time improvements with very inaccurate techniques occur. More than half the area of San Diego is covered by five northern beats which causes the average beat to be $40 \%$ larger in side dimension than the average beat that would result if these five beats and the area involved were not considered. The reduction in beat dimension would cause a decrease in apparent response time improvement.

In an attempt to reduce cycle time effects, the system accuracy and cost savings calculation were also performed for three RF channels for AVM. The cost savings under these conditions for Class I systems were doubled. The savings for Class II wexe unformly increased by about $\$ 1.8$ milin to the point where the cost of the buried magnet system was equalled, as were the costs of the Class III pulse TOA system, by the cost saving. (See Sect. VII.)
7. Los Angeles, CA. Los Angeles was analyzed separately for each of the four bureaus
（Central，South，West，Valley），which range in area from 130 to $500 \mathrm{~km}^{2}$（ 50 to 200 square miles）． Again as in the medium model caty，all of the bureaus show a 5 －year saving for most of the AVM technıques．All bureaus operate about the same number of cars，so the effect of beat size on the response time efficiency increase is greater for the larger bureaus．In overall cost savings，the Valley bureau shows the greatest saving，followed in order by the West，Central，and South Bureaus．

The AVM system accuracy and 5－year saving calculations were performed for 2 and 3 RF channels for the AVM systems for each of the bureaus．－As expected，the accuracy improved to about one－half and one－third that of the one RF channel case．The 5－year saving with 3 channels showed an increase when changing from 2 to 3 RF channels that was almost twhce that obtained in changing from 1 to 2 RF channels．The increase in accuracy leads to increased car savings， thereby reducing the effect of the constant $\mathrm{O}-\mathrm{M}$ expenses（See Sect．VIII．）

$$
\frac{\text { II. Anaheim, CA, City AVM Cost }}{\text { Benefit Analysis Tables }}
$$

Table 2－1．Anaherm，CA，City AVM Physical Parameters



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THEFL arc 36 gifis ill the fleet．
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TIE HUIEEF OF UEHICLEE OH EACH SHIFT IS：
「IFミT ミHIFT 119.14

「1®：T GHIFT MIH． 14
－EEOHI ：HIFT MAN＇ 12
－ccolo shift nill 1 e

THIFI E．HITT HAM． 19

THIFJ SHIFT HIH． $1=$

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THC LITi HUULD REOUTFE E WIDE＋EAH OF




Figure 2－1．Anahem，CA，AVM Pulse or Narrow－Band Antenna Locations


Figure 2－2．Anaheım，CA，AVM Wide－Band Antenna Locations

Table 2－2．Anaheım，CA，AVM Systems Cost Analyses

| A）AfREIII CLASS I |  |  |  |  |  | TUTHLS |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | THul | mids uF |  |  |  |  |  |
| TECHIIIUE | LTPS | CITEG | SASE | Indst | 0－11 | UnL | $\checkmark 1$ des | Paitioni |
| YEYEOAPD | 5 | 0 | 59 | 12 | 101 | 1 こ | $1-6$ | 176 |
| STiLUS HEP | 92 | 0 | 5a | 12 | 101 | 269 | 2¢3 | 203 |
| O－HCCELEFUHETEPS | 5 | $u$ | 86 | 1 | 104 | 201 | EvS | Leb |
| LEEEP HELOCIHTP | 65 | 0 | 8 | 15 | 100 | 231 | $26^{\circ}$ | Eこ6 |
| ULTFASOHIC MELO | ${ }^{+}$ | 0 | 90 | 14 | 100 | C6！ | 2ts | 200 |
| COIPAS～UTUIIETER | 53 | 3 | 90 | 11 | 102 | 261 | 270 | 200 |
| COIPASS LHEEF UEL | 6 | 6 | 96 | 15 | 10. | そそう | 299 | 2s？ |
| CIIPSS／U－SOHIC VEL | 58 | 0 | 90 | 14 | 104 | 275 | 279 | 275 |
| DHECA | 76 | 9 | 5 | 13 | 193 | $2{ }^{2} 4$ | 204 | 391 |
| LUPMI | WH1 | 4 | 75 | 15 | 143 | 298 | 307 | 306 |
| jecces | －2 | 4 | 75 | 13 | 140 | 205 | 547 | $2+5$ |
| H11－STATIOSS | 15 | $\bigcirc$ | 75 | 12 | 105 | 210 | 215 | 215 |
| DIFF OHEGP | 43 | 11 | 75 | 15 | 118 | 234 | 301 | 361 |
| SIFF LOPPA | 111 | 5 | 75 | 13 | 153 | 29\％ | 3 m | 200 |
| JIFF Fli－STA | 17 | 4 | 75 | 12 | 1 13） | 215 | 319 | 22ะ |
| PELFM OHEGA | 14 | 0 | 75 | 13 | 10.4 | 210 | E11 | c25 |
| pelfit Loprit | c1 | A | 75 | 13 | $19+$ | 218： | 213 | cı？ |
| CLASS II |  |  |  |  |  |  |  |  |
| CJPIED PES LuMFs | － | 32as | 59 | 5496 | 101 | 8392 | 8895 | －6¢6 |
| PEFLECTIHG SIGIIS | 18 | 1655 | 59 | 592 | 197 | 1927 | 1930 | 1921 |
| FEFLECTIHE KUAD | 5 | 116 | 59 | 594 | 677 | 1555 | 1568 | 1559 |
| －－HiJ PuSt | $\overline{1}$ | 1194 | 59 | 228 | 173 | 1575 | 1579 | 1569 |
| HF 1afF Pats | 6 | 124 | 59 | 66 | 117 | 375 | 478 | 369 |
| Lf post | 6 | c！ey | 54 | 228 | 173 | 1071 | 11174 | 1065 |
| LILHT／I－P FOST | － | 480 | 59 | 277 | 221 | 14.78 | 1451 | 1642 |
| SJPIES HAGMIETS | 4 | 323 | 59 | －5＂ | 100 | 11.8 | 115 | 11.92 |
| ULTRAEULIIC POST | 5 | 316 | 59 | 8830 | 197 | 1912 | $1{ }^{19} 15$ | 1966 |
| TFAFFIC SEHSOR | $\bigcirc$ | 912 | 59 | 390 | 161 | 1，78 | 1482 | 1473 |
| CLASS 111 |  |  |  |  |  |  |  |  |
| IHP－EATI FII PHHSE | 9 | 76 | 163 | 18 | 149 | 313 | 322 | 323 |
| HID－2Fiti Fil frisse | 105 | 7 a | 110 | 23 | 204 | 511 | 520 | 521 |
| FULSE $T=0-H P P$ IUML | 93 | 2c4 | 257 | 56 | 134 | 313 | 622 | 323 |
| HOISE CORPELATIOH | 29 | 29 | 257 | 14 | 178 | 516 | 519 | 529 |
| girection findep－ | 2 | 71 | ${ }^{5}$ | 16 | 154 | 219 | 300 | 305 |
| CLPASFIC IV LODPS | 3 | 2343 | 57 | 1215 | 210 | 4535 | ，535 | ． 535 |
| LFAYSIDE RADIO | 5 | 2476 | 59 | 1097 | 341 | 24.4 | 2974 | 397. |
| FHOTO～I－P DETECT | 5 | 1455 | 59 | 555 | 2 21 | 2293 | てご3 | 2¢93 |
| ULTRASOHIL DETECT | 5 | 1503 | 59 | 555 | 221 | 204\％ | 23.2 | こそって |

Table 2－3．Anaheim，CA，AVM Pollıng Cycle Min／Max Times．
cracle time in seconids to moll max rid mim units deplonej

| CLfSS I tecramipue KEYBOARD | $\begin{aligned} & \text { TOTAL } \\ & \text { FLEET } \\ & 3 \text { SL } \end{aligned}$ |  | SIMPLE |  | REDUNDEMT |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Sutc | vo4 | Ramd | SYIN | （10） | PRHD |
|  |  | 204 | $\begin{array}{ll}212 \\ 1 & 3.4 \\ \end{array}$ | 4 48 | ${ }_{1}^{2} 18$ | 23 | $\cdots$ |
| STILUS Hipe | 403 | 213 | 283 | 418 | 230 | 1 2 51 | 45 |
|  |  | 134 | 139 | 264 | 1 ＊ | 153 | $2 \%$ |
| Z－RCCEL EROXETEFS | 394 | 283 | 215 | 413 | 225 |  | 4 ＋ |
|  |  | 131 | 130 | 261 | 142 | 152 | 28 |
| LhSEP Velocimit | 398 | 210 | 218 | ${ }_{4} 16$ | 231 | 2 is | 451 |
|  |  | 1.33 | 138 | 282 | 140 | 155 | 285 |
| Lltrfsonic velo | 394 | 263 | 215 | 413 | 225 | $2+1$ | 448 |
| COHPASS－ODOHETEP | 394 |  | 1 2 2 | 261 | 142 | 15 sc | 282 |
| chers | 3 | 131 | 136 | ${ }^{+} 81$ | 1 1 4 | 14 | 48 |
| COMPASSSLASER VEL | 394 | 208 | 215 | 413 | 225 | 241 |  |
|  |  | 131 | 136 | 201 |  | 152 | 282 |
| CIPSSU－SOMIC UEL | 394 | 208 | 215 | $+13$ | 225 | 24 | 445 |
|  |  | 131 | 130 | 261 | 142 | 15 | 2 8 |
| Ofitch | 4 cs | 234 | 232 | 429 | 253 | 274 | ＋ 70 |
| LORPA | 437 | $1 \begin{aligned} & 1 \\ & 31\end{aligned}$ | $1 \begin{aligned} & 146 \\ & 243\end{aligned}$ | ¢ ${ }_{4}{ }^{36}$ | 163 2 | 173 280 | 302 |
|  |  | 14 | 150 | 275 | 171 | 280 181 | 395 |
| JECEA | ＋32 | 223 | 230 | 433 | 260 | ${ }^{2} 81$ | 486 |
|  |  | 144 | 149 | 274 | 16 | 178 | 305 |
| mil－stat ions | 38 | 205 | 213 | 410 | 2 20 | 23 | 41 |
|  |  | 130 | 13.4 | 259 | 139 | 149 | 378 |
| DIFF OIEGCA | 425 | 2 20 | 239 | 489 | 258 | 274 | 479 |
| DIFF L0FPal | $\rightarrow 37$ | 1 2 31 | 1 3 3 3 | 271 436 | 1 2 71 | 173 |  |
| DrF Lorn |  | 1 in | 150 | 275 | 171 | 181 | 310 |
| MIFF RHI－STA | － 22 | 223 | 231 | 428 | 350 | 271 | 470 |
|  |  | 181 | 1914 | 270 | 162 | 171 | 301 |
| RELAY CHIELA | 30060 | 1919 | 19193 | 13395 | 38199 | 38205 | 38.419 |
|  |  | 12120 | 12125 | 125 | 24129 | 24138 |  |
| RELPY．LORFII | 156 | ¢ 23 | ¢31 | 1029 650 | 1457 920 | 14 9 | 1678 1059 |
| CLASS II |  |  |  |  |  |  |  |
| EUPIED RES LOOPS | 394 | ${ }^{2} 08$ | 215 | 413 | 2 25 | 241 | 440 |
| FEFLECTIIG SIGRS | 394 | 1．31 | 1 2 15 15 | 2 4 4 4 | 1 2 2 | 152 241 | 282 |
|  |  | 131 | 136 | 201 | 142 |  | $\bigcirc$ |
| REFLECTING ROAD | 394 | 208 | 215 | 413 | 2 cs | 241 | 4 |
|  |  | ${ }_{2}^{1} 81$ | 136 | 251 | 14 | 15 | 3 |
| S－EARTS POST | 391 | 206 | 214 | 412 | 23 | 238 | 443 |
| hF，UHF POUST | 386 | ${ }^{1} 30$ | ${ }^{1} 3$ | 208 | 1.41 2 18 |  | 280 |
|  |  | $1 \geqslant$ | 134 | 25 | 138 | 1 183 47 | ¢ 27 |
| LF MOST | 391 | 205 | 214 | 412 | 223 | 238 | $4+3$ |
|  |  | 139 | 135 | \％ 0 | 141 |  | 230 |
| LIGET／I－R POST | 391 | 200 | 21 17 | 412 | 23 | $23 \%$ | 473 |
| SURIED MALGETS | 394 | 139 | 135 215 |  |  | $\frac{1}{2} 50$ | 2 80 |
|  |  | 131 | 130 | ¢ 61 | 142 | 1 s2 | 3 |
| ULTRHSOHIC POST | 391 | 200 | 214 | 412 | 2 c | 235 | $4+3$ |
| TPAFFIC SEASOR | 391 | 1.30 2.00 | 135 | 260 | 1 <br> 2 <br> 21 <br> 1 | ${ }_{2}^{150}$ | こ 9 |
|  |  | 130 | 135 | $\stackrel{4}{2} 6$ |  | ${ }_{1} 30$ | $\overbrace{2}^{+3}$ |

Tablé 2－4．Anaheım，CA，AVM Accuracies and Cost Benefits

| AMUREEI： |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | ， | THEO |  |  | UEHi |  | ESTIHATES |
| Clwis i mbT | IPTE | UEHICLES |  | C． |  |  | 5－EAS |
| TECIIISUE MCCL | RRC： | SAVED | 1 Hn | $11 / 4$ | 1180 | 18f | －3＞1515 |
|  | 3 | 1 | ${ }_{4}$ | $\rightarrow 1$ | 4 r | 1 ก | L－5 |
| SThlus map | 6 | 1 | 83 | 305 | 07 | 1 \％ | －＋3） |
| 2－ATCELEFUIETEPS | 64 | 1 | 43 | 95 | 9 | 14 | 231 |
| LHSEF DELOCIHTP | 13 | 1 | 74 | 49 | 07 | 11 | L45 |
| UTFHEOHIC 18LO | －11 | 1 | 198 | 105 | 06 | 10 | ＜＜t |
|  | Ev | 1 | 7 － | 5 | 65 | 11 | 215 |
| CCIIPFISE／ASEP LEL | 15 | 1 | 74 | 49 | 07 | 1 | 5 |
| CIfSSSU－SOHIC MEL | 13 | 1 | 74 | $\rightarrow$－ | $0 \%$ | $1:$ | 205 |
| OrIEG | 1600 | 4 | St14 | こロット | 00 | 511 | $v$ |
| LUPMTI | 160 | 1 | 392 | 381 | 92 | 01 | －305 |
| JECLH | 2un | 1 | ${ }^{-72}$ | －63 | 11 | y 4 | －5－10 |
| Atiostatioils | 239 | 1 | $\rightarrow 79$ | －0， | 01 | 0 O | －4 |
| SIFF DiELS | 164 | 1 | 391 | 384 | 42 | 41 | 5 |
| JIFF LJPRt | －U10 | 9 | 1u91 | 1uS＊ | 94 | 44 | 3 |
| JIFF Hi1－STA | c5u | 1 | 553 | 55 | 00 | 010 | 1 |
| PELAY OfIECH | 514 | 0 | 0307 | －115 | 94 | 00 | 1 |
| FELHP Lorent | Cum | $u$ | 2215 | 2los． | 00 | 00 | 4 |
| ULHES II |  |  |  |  |  |  |  |
| 3MFIES RES LOOFS | 16 | 1 | 73 | $4{ }^{3}$ | 27 | 11 | 520 |
| FEFLECTILG SIGHJ | 15 | 1 | 73 | ＋ | 97 | 11 | 100 |
| FEFLECTIUG POAD | 2 | 1 | 71 | ${ }^{-}$ | 0 \％ | 11 | こ510 |
| $\bigcirc \mathrm{PERHD}$ POST | 12 | 1 | 73 | － | 0 | 11 | $-0$ |
| hr，blife pust | 15 | 1 | 73 | 43 | 0 ？ | 11 | 200 |
| LF POST | 104 |  | 258 | 252 | 4 | 45 | －40 |
| LILHET－P POST | 38 | 1 | $\varepsilon_{2}$ | 30 | 0 | 1 J | 355 |
| ZUPIED HIEGUETS | ＋ | 1 | 71 | T | 07 | 11 | －uts |
| ULTPASOHIC PUST | 20 | 1 | 7. | 51 | 07 | 11 | 100 |
| TFAFFIC CEHBUF CLAOS III | 10 | 1 | 73 | ＋ | $0 \%$ | 11 | $\sim 20$ |
| H14P－JEHS FH PHHSE | 1000 | 0 | $2 \cdot 38$ | E433 | 04 | 11.1 | 0 |
| WIJ－zath Fit Phtse | 1200 | 0 | 2954 | 289 | 96 | 0 11 | 0 |
| PULEE T－OHPPPIJAE | 100 |  | $1{ }^{17}$ | 173 | 05 | ${ }^{1} 3$ | －320 |
| HOISE CUPPELETIOU | 100 | 1 | 186 | 174 | 05 | ${ }^{1}$ | －305 |
| SIPECTIOH FIMDEP CLHSS IU | 790 | 6 | 1830 | 1730 | 0 n | 04 | 0 |
| TFHFFIC LOOPS | 19 | 1 | 25 | 23 | บ | 12 | －1．3） |
| WR1 SIDE PADIO | 100 |  | 219 | 23 | 95 | 13 | －1255 |
| PHOTOSI－R JこTECT | 30 | 1 | 85 | 6 | $4:$ | 11 | 230 |
| ultarsumic jetect | 20 | 1 | 45 | － 6 | $0-$ | 11 | 030 |

III．Long Beach，CA，City AVM Cost Benefit Analysis Tables

Table 2－5．Long Beach，CA，Cıty AVM Physical Parameters
rflen is 50．z zOUAPE MILEG．
Cast hest misthice is 10 hiles．
IDORTH GOUTH IISTGHEE IS E．E HILES．
TOTAL FOAJ HILEFIGE I E EGGG HLES．
THE HBILEE OF IHTEFSECTIOHE IS E日UG．
THE ESTIMATED HUHEEF OF FORD SEGHEHTS IS 1g000：
THEFE FRE E1 CARS IH THE FLEET．
AIIJ THEFE ARE 51 mOTORCYCLES．
the huiger of vehicles oh EfCH 三hift is：
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TIFST BHIFT MIH． 16
sLudit ehift mat le

GELOHE EHIFT HIH．10
 GEFGTNAL PAGB IS PEOT：

THIFI EHIFT HA゚．1E

THIRE EHIFT HIH．IE

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THE CIT，HOULI REMUIRE 7 MIDE＋EAHID OR




Figure 2－3．Long Beach，CA，AVM Pulse or Narrow－Band Antenna Locations


Figure 2-4. Long Beach, CA, AVM Wide-Band Antenna Locations

Table 2-6. Long Beach, CA, AVM Systems Cost Analyses


Table 2-7. Long Beach, CA, AVM Polling Cycle Min/Max Times

CTCLE TIHE IM SECOHDS TO POLL hax fand min birts deployed

| CLRSS 1 TECHHICUE | torat <br> FLEET | STHC | $\begin{aligned} & \operatorname{SInPLE} \\ & \operatorname{VOL} \end{aligned}$ | FARD | SYic | RETVEHDFHT VOL | (1atis |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| KEYEOARD | $\pm 20$ | 17 c | 179 | 347 | 183 |  | 373 |
|  |  | $1{ }^{1}$ | 179 | 347 | 183 | 198 | 373 |
| STYLUS Mep | 1254 | 199 | 137 | 354 | 198 | 213 | $3 \%$ |
|  |  | 179 | 187 | 354 |  | $2{ }^{2} 13$ | 388 |
| 2-fCCELEROTETERS | 1285 | 127 | 182 | 350 | 198 | 265 | 38 |
|  |  | 175 | 182 | 350 | 190 | 2185 | 3 38 |
| LPSER MELOCINTR | 12.40 | 177 | 185 | 352 352 | 194 194 | 269 269 | 384 384 |
| Llfasonic velo | 12.25 | 177 | 185 182 | 352 350 | 196 | 263 <br> 205 <br> 15 | 3\% |
| UTRAsonic velo |  | 175 | 182 | 350 | 1-90 | 285 | $3 \cong$ |
| COTEPSS/ODOHETER | 12-25 | 175 | 182 | 350 | 198 | 205 | 30 |
|  |  | 175 | 182 | 350 | 199 | 265 | 380 |
| COTPRSS/LASER VEL | 12.25 | 1.75 | 132 | 358 | 1.98 | 205 | \% |
|  |  | 175 | 182 | 350 | 198 | 205 | 388 |
| CPPSSN-SONIC VEL | 12.25 | 175 | 132 | 350 | 190 | 265 | - 20 |
|  |  | 175 | 182 | 358 | 198 | 20 | 8 |
| OTECA | 1322 | 199 | 190 | 3104 | 218 | 2.33 | $\begin{array}{r}467 \\ 4 \\ \hline\end{array}$ |
| LORSA | 1359 | 1.39 1.94 | 1 <br> 1 <br> 296 <br> 182 | 3.64 3.69 | 2.18 2.28 | 2.33 | 767 4.18 |
| LCand |  | $1 \mathrm{a4}$ | 202 | 389 | 23 | - 43 | 413 |
| DECCA | 1344 | 1.92 | 1.99 | 367 | 224 | 2-39 | $\div 14$ |
|  |  | 1.92 | 199 | 3 nt | 2.24 | 2.39 | 414 |
| fil-Stations | 1210 | 173 | 180 | 348 | 1.86 | ? ${ }^{\text {al }}$ | 375 |
|  |  | 1.73 | 188 | 3.48 | 1.80 | 2-61 | 375 |
| DIFF OTEGA | 1322 | 1.89 | 190 | 3.64 | 2.18 | 2.33 | 4 97 |
| DIFF. LORFA | 1359 | 1.89 1.94 | 1.96 2.92 | 3.64 309 | - 18 | ${ }_{2} 33$ |  |
| Difr. |  | 1.94 | 2.02 | 3.9 | 2-23 | 2-43 | 13 |
| DIFF RUT-STA | 1314 | 183 | 195 | 363 | 216 | 230 | 05 |
| DIF M1-ST | 13. | 1.83 | 195 | 363 | 216 | $2-30$ | 405 |
| Rg_at OfEGA | 1131-28 | 161.68 | 161.68 | 16335 | 32160 | 32175 | 32350 |
|  |  | 16160 | 16168 | 16335 | 3 Fl 60 | 321.75 |  |
| Relay lorfit | +853 | $\begin{aligned} & 693 \\ & 693 \end{aligned}$ | $\begin{aligned} & 701 \\ & 701 \end{aligned}$ | 868 868 | 1227 | 12 124 | $\begin{aligned} & 1417 \\ & 1417 \end{aligned}$ |
| CLASS II <br> ELRIED RES LOOPS | 1225 | 1.75 | 1.82 | 350 | 190 | 2.85 | 320 |
|  |  | 1.75 | 182 | 350 | 180 | 208 |  |
| REFLECTING SIGNS | 1225 | 175 | 132 | 350 | 190 | ${ }^{2} 05$ | 380 |
| Reflecting rond | 1285 | 1.75 1.75 | 1.82 | 350 350 | 190 190 | ${ }^{2} 85$ | 380 |
|  |  | 175 | 1.82 | 350 | 199 | 205 | 380 |
| X-BRHLD POST | 1217 | 1.74 | 1.81 | 3.49 | 188 | 203 | 378 |
|  |  | 174 | 1.81 | 349 | 183 | 208 | 375 |
| HF, MF POST | 12 82 | 172 | 1.79 | 347 | 183 | 198 | 373 |
|  |  | 1.72 1.74 | 1.79 1.81 | 347 349 | 183 188 | - | 373 378 |
| LF POST | 1217 | 1.74 174 | 1.81 1.81 | 349 549 | ${ }_{1}^{1} 83$ | $$ |  |
| LIEKT/I-R POST | 1217 | 174 | 1.81 | 349 | 1 \% | 203 | 378 |
|  |  | 174 | 1.81 | 349 350 | 188 189 | ${ }_{2}^{203}$ | 378 |
| BMRIED MFGGTETS | 1235 | 175 | 1.82 | 359 | 198 198 | ${ }^{2} 08$ | $3 \%$ |
| Letrasonic post | 1217 | 174 | 1.81 | 349 | 188 | ¢ 83 | 378 |
|  |  | 174 | 181 | 349 | 18 | 203 | 373 |
| TRAFFIC SEISSOR | 1217 | 174 | 1.81 | 349 | 189 | 283 | 378 |
|  |  | 1.74 | 181 | 349 | 1 8, | 203 | 378 |

Table 2-8. Long Beach, CA, AVM Accuracies and Cost Benefits

$\frac{\text { IV．Montclair，CA，City AVM Cost }}{\text { Benefit Analysis Tables }}$


Figure 2－5．Montclatr，CA，AVM Pulse or Narrow－Band Antenna Locations


Figure 2－6．Montclair，CA，AVM Wide－Band Antenna Locations

Table 2－9．Montclair，CA，City AVM Physical Parameters

HFEA IS 5．E GOUARE MILES．
LAST HEST DISTAHCE IS 2.3 HILES． HOFTH EOUTH IISTANCE I亏 z．5 HILES． total rofy hileage is 6r miles． THE HUIEER OF INTERSECTIONS IS 338.
fhe estimated nuiger of pohd segients is 50e：
THEPE RFE 10 GARS LIf THE FLEET．
Ald THEPE FRE G HOTOPCYCLES．
THE HUITEER OF UEHICLES OH EACH SHIFT IS：
FIF＇S SHIFT tAR． 5

IIFST EHIFT MIH． 4

EECDHD SHIFT MAK． 5

SCCOHD SHIFT MIN． 4

THIPD SHIFT HAS＇． 7

THIFD SHIFT MIN．？

THE HUIEER OF HIFFRTCHEFS IS 1

THE CIT＇HOULI FEOUIPE＝MIDE＋EANI OP FILLSE RHTEHHM SITES RHID 5 MAFPOUN BAHII


Table 2－10．Montclair，CA，AVM Systems Cost Analyses

| $\begin{aligned} & \text { HuITCLAII } \\ & \text { CCASS I } \end{aligned}$ |  |  |  |  |  | Tutals |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | THnus | Fins of | $\pm$ |  |  |  |  |
| techargue | CARS | SITES | EASE | If＇st | 0－11 | 150 L | S．14C | Ferijoll |
| YEIEORPD | 2 | 0 | 45 | 11 | 101 | 159 | 157 | 15 |
| Sticus liap | 20 | 0 | $\rightarrow 5$ | 11 | 101 | 133 | 132 | 132 |
| 2－ACCELEPOIETERS | 15 | 0 | 63 | 11 | 101 | 196 | 209 | 203 |
| LRSEP IELOCIMEP | 15 | ${ }^{6}$ | 70 | 12 | 162 | 203 | 505 | Eu4 |
| ULTPRSUHIC LIELU | 15 | 9 | $7{ }^{6}$ | 11 | 112 | 197 | 109 | 1.9 |
| CUIPHOSCODOTETEP | 15 | 4 | 70 | 11 | 101 | 197 | Lu3 | 199 |
| CUITHSNOLASER NEL | 19 | ${ }_{1}$ | ？ 0 | 12 | 191 | 203 | 45 | 30 |
| CIFPS／U－SONIC VEL | 10 | ${ }^{11}$ | 79 | 11 | 191 | 200 | －U2 | 301 |
| Blach | ${ }^{-}$ | 4 | 55 | 11 | 101 | 196 | 148 | 198 |
| L0Rar | c | 9 | 55 | 11 | 141 | 14 | 139 | 178 |
| DECCA | 12 | 0 | 55 | 11 | 151 | 130 | 183 | 132 |
| gui－starious | － | 9 | 55 | 11 | 1111 | 172 | 17. | 17゙ー |
| DIFF．OHEEA | 27 | 6 | 55 | 11 | 101 | 198 | 198 | $1 い$ |
| DIFF LDREAI | 23 | U | 55 | 11 | 101 | 197 | 179 | 14 |
| DIFF\％AII－STA | 5 | 1 | 55 | 11 | 191 | 173 | 175 | 17t |
| PELA，UliEGA | n | 4 | 55 | 11 | 101 | 174 | 173 | 175 |
| PELA，LOPA | 0 | $v$ | SS | 11 | 161 | 175 | 17. | $1{ }^{\text {\％}}$ |
| CLFSS II |  |  |  |  |  |  |  |  |
| SUPIED RES LOOPS | $z$ | 110 | 45 | 147 | 101 | 454 | －55 | $\rightarrow 53$ |
| PEFLECTING SIGIS | 5 | 56 | 45 | 42 | 106 | 255 | 256 | 253 |
| FEFLECTING ROAD | 2 | 7 | $\rightarrow 5$ | 48 | 131 | 232 | 233 | －35 |
| －－EAHD POST | 2 | 78 | $\square$ | 20 | 106 | 257 | 255 | $\leq 56$ |
| HF，UHF POST |  | 9 | 45 | 15 | 1152 | 170 | 174 | 111 |
| LF POST | 2 | －3 | 75 | 20 | 116 | 222 | 223 | 220 |
| LIGHT／IMP POST | 11 c | 34 | $\rightarrow 5$ | 30 | 103 | 20 | 231 | $21^{9}$ |
| BUPIED MPGHETS | 1 | 11 | 45 | 33 | 109 | $1{ }^{19}$ | 132 | 14y |
| ULTPHSOHIC POST | 2 | 4.4 | 45 | 54 | 186 | 251 | 252 | 34 |
| TPHFFIC SENSOR CLASS III | 2 | $\rightarrow 9$ | 45 | 31 | 101 | 227 | 23s | cat |
| NRR－ERHD FII PHiRSE | 3 | 24 | 54 | 11 | 103 | 193 | 201 | ごく |
| HID－prip FM Phise | 39 | 35 | 72 | 10 | 2ue | 353 | 350 | 35 |
| FUSE T－0－APPEVHL | c6 | 70 | 143 | 24 | 17 | 741 | $\cdots$ | $4{ }^{4}$ |
| HOISE COPRELAEIOH | 3 | 290 | 143 | 16 | 176 | 374 | 375 | 375 |
| DIFECTIDI FINDEP | 1 | 79 | 35 | 15 | 15.4 | $23_{4}$ | ct | 282 |
| CLASSE IU |  |  |  |  |  |  |  |  |
| TRAFFIC LOOPS HRYSIDE PADIO | 1 | 229 155 | 45 +5 | 103 | 109 | ＋85 | 465 | 485 |
| PHOTOI－R DETECT | 2 | 117 | 45 | 49 | 109 | 320 | 320 | 720 |
| ULTEASOMIC JETECT | 2 | 1 L | ¢5 | 49 | 109 | 32， | 3 34 | －24 |

Table 2－11．Montclair，CA，AVM Polling Cycle Min／Max Times

CYCLE TIME IN SECOMDS TO POLL MAX AND HIN UNITS DEPLOTED

| CLess I TECHMIOUE | total fleEt | \＄750 | $\begin{gathered} \text { SITPLE } \\ \text { IDOL } \\ \hline \end{gathered}$ | Rend | SYic | REDUUNEAT vot | Pravd |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| LEYBORRD | 107 | 075 | c 77 | 149 | 080 | 084 | 153 |
|  |  | a 43 | 844 | 085 | 046 | 048 | 050 |
| stylus mep | 112 | 078 | 080 | 152 | 087 | 091 | 164 |
|  |  | 045 | 046 | 987 | － 59 | 0 家 |  |
| 2－FACCELEROHLETERS | 189 | 07 | 978 | 158 | 083 | 987 | 161 |
|  |  | 04 | 045 | 026 | 048 | － 50 | 092 |
| LASER VELOGIMTR | 111 | 078 | C 79 | 151 | 085 | 089 | 102 |
|  |  | 64 | 045 | 88 | 049 | － 51 |  |
| ULTPASOMIC UELO | 169 | 677 | 078 | 150 | 983 | 687 0 | 181 |
|  |  | $0{ }_{0}^{0} 4$ | 045 | 986 |  | 950 |  |
| COTPRSS－ODOHITER | 1.69 | 0 77 | ¢ 88 | $\begin{array}{ll}150 \\ 9 & 36\end{array}$ | 083 043 | 687 0.59 | 181 981 |
| COMPASSLASER リEL | 109 | 077 | 078 | 150 | － 83 | 487 | 151 |
|  |  | 0.44 | 945 | 08 | 048 | 450 | 042 |
| CTASSTU－SOHILC UEL | 189 | 977 | 078 | 159 | － 83 | 087 | 101 |
|  |  | 0.44 | 945 | 080 | 049 | 050 |  |
| OTEER | 118 | 983 | 085 | 156 | 095 | 989 | 173 |
|  |  | $0 \cdot 4$ | 048 | 989 | 054 | 057 | 097 |
| LORAS | 1.21 | 085 | 687 | 1.59 | 180 | 194 | ？ |
|  |  | 049 | － 50 | a 41 | B 57 | － 59 | 101 |
| DECCA | 120 | 084 | （0） 8 | 158 | 0.43 | 1 㫜 | 175 |
|  |  | 048 | 0.49 | 998 | 050 | 058 | 1.00 |
| RM－STATIOHS | 1 日3 | 0 <br> 0 <br> 0 <br> 13 | 0.78 0.44 | 149 985 | 0.31 0.46 | 985 848 | ${ }^{1} 591$ |
| DIFF．OHECA | 118 | 0.83 | －85 | 1.50 | 095 | 999 | 173 |
|  |  | 047 | 048 | 439 | $0{ }^{5}$ | 957 |  |
| DIff．LORew | 1.21 | 085 | 687 | 159 | 108 | 184 | 178 |
|  |  | 949 | － 59 | $4{ }^{1} 1$ | $05 ?$ | 959 | 181 |
| DIFF FHT－STA | 117 | 583 | 484 | 156 | 09.4 | 99 |  |
|  |  | 3.47 | 948 | 989 | 954 | 956 |  |
| KELFY OHECA | 10100 | 70.79 | 7972 | 71.4 | 14079 | 14974 | 14148 |
|  |  | 40.40 | 4041 | 4082 | 69 40 | 3642 | 8084 |
| RELIMY LGRFH | 433 | $303$ | $\begin{aligned} & 305 \\ & 174 \end{aligned}$ | 377 <br>  | $\begin{aligned} & 537 \\ & 307 \end{aligned}$ | $\begin{gathered} 5 \\ 3 \end{gathered}$ | $\begin{aligned} & 614 \\ & 3 \\ & 51 \end{aligned}$ |
| Class II <br> EURIED RES．LCOPS： | 106 | 174 | 070 |  | 078 | 082 | 58 |
| EURIED REG．LCOPS |  | 042 | 943 | 0 ¢ 5 | 0.5 | 647 |  |
| REFLECTING SIGHS | 108 | 074 | 976 | 148 | 978 | 08 | 150 |
|  |  | 342 | $0{ }^{-3}$ | 085 | 045 | $0 \rightarrow 7$ | 089 |
| Reflectint rofid | 106 | 074 | b 76 | 148 | 078 | 082 |  |
|  |  | 642 | 943 | 885 | 045 | 647 |  |
| X－EARID POST | 1 uo | 97 | 970 | $\begin{array}{ll}1 \\ 9 & -8\end{array}$ | 0.78 0 | 98 | 150 |
| MF，UAF POST | 185 | 4 42 | $\bigcirc{ }^{9} 43$ | $\begin{array}{ll}9 & 4 \\ 147\end{array}$ | 9 ${ }^{0} 9$ | 98 | ${ }_{19}^{98}$ |
|  |  | 64 | 043 | $\square 8$ | ก44 | ¢ 9 | 008 |
| LF POST | 100 | 974 | 970 |  | 975 | 0 － |  |
|  |  | 9 92 | ${ }_{9}^{9} 76$ |  | 4 4 75 | 9 CH |  |
| LIGHT／I－R PGST | 105 | 9 24 | 9 9 9 | ${ }_{6}^{1}{ }^{45}$ | － 0 | 0.7 | $1{ }^{1}$ |
| Bupied magnets | 106 | 0 c 4 | 976 | $1+8$ | 9－ | ¢ | 156 |
|  |  | 042 | 0.3 | 4 | 95 | ${ }_{0}+{ }^{+}$ | 434 |
| ULTRASOHIC FOST | 106 | $0{ }^{0} 7$ | 976 | $1+3$ | $0{ }^{1}$ | 00 | 156 |
| TRAFFIC SENSCR | 10 | 074 | 076 | 13 | 0.78 | 48 | 15 |
|  |  | 0 － 2 | 043 | 685 | 045 | $4{ }^{4}$ | $0 \%$ |

Table 2－12．Montclair，CA，AVM Accuracies and Cost Benefits

| TUPITELAP | SNTEA MCCUPAEIES OD MEAICLES RHD |  |  |  | ESTIMATED |  | \＄1000 | SRUIFIGS cotitiated |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| CLASS I ULTI | trte | UEHICLES |  | RCY |  |  |  |  |
| TECrilitue ACCi |  | SHIED | 1192 | HIN | HPC |  | 1 t | FAJIILC |
| l＇exobrp | 3 | ${ }^{6}$ | 38 | 34 | －き |  | こ | むひ |
| STILUS IERP | 30 | 1 | 77 | $\checkmark$ | 93 |  | 3 | － |
| LHCCELEPQUETEPS | 34 | 1 | 81 | 3 | 02 |  | 3 | 50 |
| LFSEP JELOCIHTR | 13 | $a$ | \％ | 3 | 62 |  | $\cdots$ | 210 |
| ULTRFSOHIC MELO | 40 | 9 | 103 | 140 | 92 |  | 3 | 35 |
| COHPASS／OJOUETEP | 29 | 6 | 59 | 4 | 02 |  | － | C65 |
| COHPTASS／LACEP UEL | 15 | B | $\approx 9$ | $3{ }^{3}$ | 0 こ |  | ${ }^{+}$ | 205 |
| CIPSSU－OUHIC UEL | 17 | 1 | $\rightarrow 3$ | － | 02 |  |  | 20 |
| CIIEGA | 1500 | ¢ | \％31 | 3664 | 06 |  | 13 | 9 |
| 1．UPAI | 1 Eb | ${ }_{0}$ | $3{ }^{3}$ | 26 | 130 |  | 4 | 4 |
| 3itca | 290 | 4 | 454 | 442 | $\square{ }^{6}$ |  | 5．t | 0 |
| Ant－STATIOHS | 300 | 0 | 450 | 4.0 | 96 |  | 10 | 4 |
| JIFF OlIEGA | 160 | 6 | 375 | 350 | ${ }^{9} 0$ |  | ¢ | 0 |
| 3ITF LOPMII | 400 | 9 | 983 | 945 | 09 |  | 10 | $\pm$ |
| JiFF Rll－3TA | 350 | 1 | 545 | 532 | 69 |  | 10 | 0 |
| REEAP OHECA | 560 | 0 | 2440 | 13 抱 | 90 |  | 4 | 0 |
| PELAC LOFAI | 300 | 9 | 2110 | 205 | $0 \cdot$ |  | 15 | $\checkmark$ |
| Class 11 |  |  |  |  |  |  |  |  |
| SLPIES RES LOOPS | 16 | 1 | 27 | 27 | 92 |  | ＂ | －0， |
| PEFLECTIHG SIGHS | 14 | $\square$ | 27 | 27 | 9 |  | 4 | －2－5 |
| TEFLECTIIS POAI | 3 | 9 | 27 | 15 | 52 |  | 4 | －2， 5 |
|  | 12 | 9 | 32 | 32 | ${ }^{13}$ |  | ＊ | －230 |
| HF LHF PGST | 15 | U | 39 | こ\％ | ¢ |  | 4 | 210 |
| IT POST | 140 | 9 | 245 | 239 | ${ }^{5}$ |  | 5 | － 0 |
| LIGRY／I－F POET | 30 | 1 | \％ | 万\％ | ${ }^{1} 3$ |  | 13 | －320 |
| उupIES JHGMETS |  | 4 | 27 | 15 | 03 |  | ） | －250 |
| UTPALOHIC POST | 20 | 9 | so | ＋ | ${ }^{3}$ |  | I | －20 |
| TPFFFIC OEHSOP | 10 | 15 | 67 | ET | 42 |  | J | 205 |
|  |  |  |  |  |  |  |  |  |
| IHR－ERIII FII PHASE | 1206 | 0 | 2389 | 23969 | ${ }_{3} 9$ |  | 0 | b |
| W13－ERNY FII PHACE | 1200 100 | 0 0 | 2814 | －10． | ${ }^{81}$ |  | 1 | $-315$ |
| FULSE T－D－AFPIUAL | 100 100 | 0 | 163 | 133 | 51 |  | 0． 1 | －319 |
| JIFECTILH FILIJER | 704 | 6 | $1-43$ | 1077 | 04 |  | 6 | 4 |
| CLA3－${ }^{111}$ |  |  |  |  |  |  |  | －2．5 |
| TFRFFIC LDOFS | 140 14 |  | 836 |  |  |  |  | 0 |
| UnH1SIDE RAJIO | 1 Ev | 9 | 630 | ざった | 95 |  |  |  |
| PHOTU\I－P JETECT | 20 | 9 | 4 | $4{ }^{3}$ | ${ }_{0}^{2}$ |  | 4 | $-2-5$ |

V．Monterey Park，CA，City Cost Benefit Analysis Tables

Table 2－13．Monterey Park，CA，City AVM Physical Parameters

APEE IS 7.3 gounre hiles．
EAST WEST DIETfHCE IS 4.6 MILES．
NORTH SOUTH HİTAITCE IS 3 MILES．
TOTAL ROAI HILEAGE I 2151 HILES．
THE NUIRER OF IMTEREECTIOHS IS 5ge．
THE ESTIMATED HUMBEF OF FOAD GEGMEATE is Eec：
THERE RFE 15 CfPS IN THE FLEET．
FITI THERE RRE 9 tIOTOFCYCLES．
THC HUIBER GF UEHICLES ON ERCH SHIFT IS：
FIRET SHIFT HAR：－ 14

FIFET BHIFT HIN． 4

EECOLID SHIFT MAR： 14

SECOHI SHIFT MIN． 4

THIRE SHIFT HAX． 14

THIRE BHIFT HIH． 4
THE HUIBER OF SISFRTCHEPS IS 1

THE CITY WOULI REOUIRE \＆WIDEPBHID OF
pulse fittentif sites fid 5 haffoll bend
FH AHTENIA SITES FOR 7 RHIS 3 IILE PRIIUS CDUEPRGE．


Figure 2－7．Monterey Park，CA，AVM Pulse or Narrow－Band Antennas


Figure 2－8，Monterey Park，CA，AVM Wide－Band Antenna Locations

Table 2－14．Monterey Park，CA，AVM Systems Cost Analyses

| HOMTEFE；FACH Chiss 1 |  |  |  |  |  |  | tothls |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| recminue |  |  |  | Hist |  |  | OHC | pancurl |
|  | ${ }^{3}$ | ， | $\stackrel{\cdot}{8}$ | 11 | ${ }_{131}$ | 104 | 101 | 151 |
| ${ }_{\text {STHCL }}$ |  | ソ | ${ }^{-3}$ | ${ }_{12}^{12}$ | 1012 | 2012 |  | 15 |
| LHSEP UELOCIITR | ＝ | v | 7 | 13 | Ius | c19 | zar | $2{ }^{2}$ |
| GTTPASOHIC UELO | 5 |  | 75 | 12 | 103 | 211 | 214 | 213 |
| IPPASSJOIOHLIETER | 2 | $0$ | 75 | 11 | 191 | 211 | 214 | 12 |
| IPMSS／LASEP |  |  | 75 |  | \％ |  |  |  |
|  |  |  | 55 | 12 | 152 | 215 | 12 | 17 |
| Ellegh | －1 |  | 0 | 12 | 1192 | c10 | 229 | 219 |
| falt | － | $0$ | s | 12 | 142 | 172 | cat |  |
|  | ： | ： | so | H | 边 | 192 | \％ | ＋5 |
| Hilsinflilis | －1 |  | S |  | 1w | 1210 | c19 |  |
| IIfF．Lopart | 72 |  | $\stackrel{\square}{*}$ | 12 | 102 | $21^{-}$ | 25 | 221 |
| 3ifF mill | $\stackrel{\rightharpoonup}{*}$ | － | su | ${ }_{1}$ | 151 | $18{ }^{1}$ | 10. | 150 |
| FELH，Ulleg | z | ง | EU | 12 | 192 | 133 | 161 | \％ |
| LH，LuFHi | y |  | ${ }^{\text {d }}$ | 12 | 192 | 13. | 16 | 18． |
| EUPIEP FES LOOPS |  |  |  | 3.8 |  |  | Tu1 | son |
|  | 3 | ${ }_{10} 1$ | 4 | $\frac{82}{11}$ | ${ }_{159}$ | ${ }_{263}$ | ${ }^{321}$ | 380 |
| SEAPHP POST | $\stackrel{3}{3}$ | 135 | $\rightarrow$ | 33 | 119 | 337 | $3{ }^{3}$ | 35 |
| HFP， | $\stackrel{3}{2}$ | 15 | $\stackrel{\square}{8}$ | 18 | 116 | 10 | 134 | 15 |
| Lichitiop fust | S |  | ＋ | 3 | 116 | 2ta | － |  |
| SUf IEP IIMGGILTS | 2 | 9 | 43 | 51 | 160 | 23 | 224 | 226 |
| TRHFFIC | $\stackrel{3}{3}$ | 1 | 43 | ${ }_{4}$ | ${ }_{109}$ | 275 | －${ }^{315}$ | 370 |
| 511 |  |  |  |  |  |  |  |  |
|  |  | $\stackrel{2}{ }$ | ${ }^{1}$ | 12 | 10 | ${ }_{5}^{218}$ | 216 | 210 |
|  |  | － |  | 25 |  |  | 9 |  |
| ISE COPFELATIOA | 12 |  | 175 | 16 |  | －11 | －12 | 13 |
| MiPECTIOM FIMDER | 1 | 19 | 41 | 15 | 154 | \％ 4 | －sy | $4{ }^{\circ}$ |
| TPAFFIC Loops |  |  |  |  |  |  |  |  |
| WSILE PRDIO | 2 | 234 | 48 | 104 | 121 | 50 | 503 | 5ud |
| Prowoile ietect | 冡 | ${ }_{1}^{137}$ | ${ }_{-8}^{8}$ | 79 | 118 | －30 | ${ }_{4} 56$ | $\xrightarrow[-30]{ }$ |

1．OTITPE，FHF1

VI. Pasadena, CA, City AVM Cost Benefit Analysis Tables

Table 2-17. Pasadena, CA, City AVM Physical Parameters
ffef lis es scuafe hiles. easi hest instance is 6 hiles.

MORTH SUUTH MISTANCE 13 इ MILES.
rothl poal milefice is 650 miles. .
the nuilee of intefsections is 1ega.
the estilited humief of ford seghents is 2720 : thefe fre 55 Chrs im the fleet.

Fitl Thefe hpe a motopcicleg.
THE HUIEEF OF UEHICLES OH EACH SHIFT IS:
FIFET SHIFT HAX. 10

ГIFET EHIFT HIH- 10

SCOOHIS SHIFT MAY. 19

EECOHT SHIFT HIH. 10

THIRII SHIFT MAス. 19

THIPI SHIFT HIN. 19

THE HUILEF OF DISFRTCHEPS I* 1

THL GITi HUULT FEOUIRE 3 HIDE+BRHI DR FILLSE RITTEIIIG SITES GND 7 NAREOH BRIID FII FMTEIHIA SITES FOF 3 atil 2 mile fadius covepage.

## Table 2-18, Pasadena, CA, AVM Systems Cost Analyses




Figure 2-9. Pasadena, CA, AVM Pulse or Narrow-Band Antenna Locations


Figure 2-10. Pasadena, CA, AVM Wide-Band Antenna Locations

Table 2－19．Pasadena，CA，AVM Polling Cycle Min／Max Times

CYCLE TIAE IN SECONDS TO POLL MAX FATD MIN UTIITS DEPLOYED

| CLASS I TECHAICUE | TOTAL fleET | SYuc | EITFLE MOL | RRHD | SY4， | FEDCHMPRTI yOL | PRHD |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| KEYBORRD | 370 | 107 | $1 \cdot 11$ | 315 | 115 | 123 | 231 |
|  |  | 187 | 111 | 215 | 115 | 123 | E 31 |
| STYLUS HAP | 392 | 112 | 1.16 | $2 \%$ | 12.4 | 13 | 240 |
|  |  | 112 | 1 is | 20 | 124 | 138 | 240 |
| 2－fCCELEROMETERS | 383 | 189 | 113 | 21i | 112 | 127 | 235 |
|  |  |  | 113 | 217 |  |  | 235 |
| LASER VELOCIMTR | 387 | 111 | 115 | 219 | 121 | 129 | ${ }^{2} 37$ |
|  |  | 111 | 115 | ${ }^{2} 14$ | $1{ }_{1} 1$ | 129 | 237 |
| LLTRRSOMIC BCLO | 383 | 189 | 113 | 217 | 119 | 127 | 235 |
|  |  | 109 | 113 | 217 | 1.19 | 127 | 235 |
| COHPASS ODOMETEF | 383 | 1 199 | 113 | 217 | 119 | $12 \%$ | 235 |
| COMPRESSLASER UEL | 383 | 1 109 109 | 1.13 1.13 | 217 | 1.19 | 127 | 3.5 |
| corprsskislr vel |  | 10 | 113 | ¢ 17 |  | 127 | c |
| CIPSS－U－SOHIC UEL | 333 | 189 | 113 | 217 |  | 127 | 235 |
|  |  | 109 | 113 | 217 |  | 127 | 235 |
| OHEGA | 413 | 113 | 122 | 220 |  | 144 | \％ |
|  |  | 118 | 1 ¢ | $2{ }^{2}$ | 130 | 1. | 2－53 |
| LORAH | $+25$ | 121 | 125 | 289 | 143 | 1.51 | 253 |
|  |  | 121 | 125 | 229 |  | 151 | 25 |
| deccea | － 20 | 129 | 124 | 2 cs | 198 | $1{ }_{1}^{18}$ | 256 |
|  |  | 123 | 124 | 288 | 1.0 | 18 | 25 |
| fti－STATIONS | 378 | 108 1.63 | 112 12 | 216 | 118 | 128 | 23 |
| DIFF OHECR | 413 | 113 | 122 | 226 | 136 | 1.84 | 2 5 |
|  |  | 1.18 | 122 | 230 | 136 | 14 | $2{ }^{5}$ |
| DIFF．LORAN | 4＊\％ | 121 | 125 | 23 | 143 | 151 | 259 |
| DIFF PM1－STA | 411 | 121 | $12{ }_{1}$ | a 29 | 143 | 151 | 259 |
|  |  |  | 121 | 225 |  | ${ }_{1}^{1-3}$ | ${ }_{5} 51$ |
| RELAY OMEGA | 35350 | 10198 | 1018 | 10298 | 20106 | 20149 | 242 16 |
|  |  | 101.63 | 10164 | 182.68 | 20180 | 2916 | 26216 |
| RELA「 LORAH | 1517 | $\begin{array}{r} 433 \\ +33 \end{array}$ | 437 +3 | $541$ | 76 7 | 75 | $03$ |
| class II <br> BLRIED RES LOOPS | 378 | 188 | 112 | 210 |  |  |  |
|  |  | 143 | 112 | 316 |  | 12 | 令 |
| REFLECTING SIGAS | 373 | 188 | 1.12 | 210 |  | 12. | 23 |
|  |  | $1{ }^{1}$ | 112 | 216 |  | 12 | き |
| REFLECTIKS PDAD | 370 | 108 | 112 | 210 |  | 12 | 2 2 |
| X－BARED POST | 370 | 1.88 | $\begin{array}{ll}1 & 12 \\ 1 & 11 \\ 1 & 11\end{array}$ | 2．10 |  | 12 | $\approx$ |
|  |  | 1 u7 | 111 | 315 | 115 | 123 | 2 31 |
| hr，Mry post | 371 | 146 | 110 | 214 | 112 | 120 | 2 |
|  |  | 160 | 110 | 214 |  | 130 | 2 |
| LF post | 370 | 1.67 | 111 | 215 |  |  | 431 |
| LIGHT／I－R POST | 2 T | 1 1 | $\begin{array}{lll}1 & 11 \\ 1 & 11\end{array}$ | 2 215 215 |  | 123 | 231 |
|  |  | 197 | 111 | 215 |  | 12 | $\stackrel{31}{2}$ |
| SURIED MAGMETS | 378 | 168 | 112 | 2 Io | 110 | 12 | 2 ๕ |
|  |  | 108 | 112 | 216 |  | 124 | C 3c |
| U．trasonic post | 370 | 107 | 111 | 215 | 1.15 | 123 | $\leq 31$ |
|  |  | 1 日r | 1.11 | 215 | 1.15 | 123 | 231 |
| TPAFFIC SEISOR | 370 | 1 bl | 111 | 215 |  | 120 | 231 |
|  |  | $1 \mathrm{\theta}$ | $1 \cdot 11$ | ＊ 15 | 115 | － 23 | － 31 |

Table 2－20．Pasadena，CA，AVM Accuracies
and Cost Benefits

| Siotersmer | IEN RO | $\begin{gathered} \text { CCUFACIES } \\ \text { THEO } \end{gathered}$ | （1），VE | $E S \text { END }$ | $\begin{aligned} & \text { ESTIM } \\ & \text { VEHI } \end{aligned}$ | 3 \＄1tu9 | SRUIMES ESTIIATE |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Class i ulti | HTE | 1ehictes |  | C． |  |  | 5－1ERP |
| TECAIIVUE RCCL | PRC | －HIE3 | 119 | 1114 | 119 | Hir | 3H1ftG |
| FEYEOMP5 | 33 | 1 | 90 | व） | 05 | 45 | 120 |
| STYLus lihp | 60 | 1 | $-1$ | －a | 45 | 4 | 13 |
| 2－HCCELEPOHETEFS | $\bigcirc$ | 1 | 4 | 4 | 45 | \％ | $\underline{1} 5$ |
| LHEEP VELOCILITP | 13 | $!$ | 11 | $-1$ | $0 \cdot$ | \％ | 0 |
| ULTTHSUHIC JELO | 40 | 1 | 10. | 16. | 勺 5 | 55 | $\underline{155}$ |
| CUFASSS，ODOTETEP | Et | 1 | 511 | Gu | ${ }^{3} 5$ | 0 ¢ | － 6 |
| COIPHSSLRASEP VEL | 15 | 1 | 40 | 49 | 00 | ＊ |  |
| CILPSS／U－SOPIE JEL | 17 | 1 | 4 | － | 96 | 90 | 9 |
| OHEGA | 16\％） | 0 | 2310 | ง216 | 0.0 | $0 \cdot$ | 0 |
| LOPM ${ }^{\text {a }}$ | 160 | C | －31 | 331 | 41 | 41 | 0 |
| 2ECCE | 2945 | $v$ | 4 | － 6 ¢ | 05 | 4 | $v$ |
| Pal－Stutions | 2ea | 0 | ＋50 | ¢ | 40 | 0 | 0 |
| DIFF OIIEGH | 15 t | 0 | 331 | $\cdots 1$ | 91 | 41 | 5 |
| JiFF Lerput | 704 | 0 | 1050 | 1050 | 00 | 014 | ${ }^{1}$ |
| JIFF FIS－STA | 250 | 4 | 55\％ |  | $0{ }^{0}$ | 01 | ${ }^{3}$ |
| RELM\％WJELH | 5 50 | 5 | 3460 | O406 | f1 | 11 u | 1 |
| PELPT／LORfid | 0 Eus | 4 | E147 | 2147 | 4 | เ 0 | $\checkmark$ |
| CLASS 11 |  |  |  |  |  |  |  |
| ExPLEg PES LCOPS | 10 | 1 | 4 | 4 | ก10 | 00 | 55 |
| PEFLECTING SIGHS | 10 | 1 | 4 s | － | 40 | 40 | －\％ |
| REFLECTIHG PGAT | 3 | 1 | 39 | 32 | 4 c | 00 | ！1－1 |
| S－3plis post | 12 | 1 | $4{ }^{4}$ | $\cdots$ | 6 C | 0 | $\underline{185}$ |
| HF，DHF PRIST | 15 | 1 | 40 | $-4$ | $f_{1} 0$ | 0 | 30 |
| LF Fós | 170 | 1 | CW9 | 25 | 113 | ¢ 3 | H2u |
| LICHT／I－R POST | 30 | 1 | $\rightarrow 7$ | 79 | U 5 | 45 | 200 |
| SUPIEJ MACIETETS | $\stackrel{ }{ }$ | 1 | ？ | 3 | 00 | 0 O | 511 |
| ULTPACONIC POST | C0 | 1 | 54 | 50 | 0 | UE | $\pm 5$ |
| TRRFFIC SEHEOF． | 10 | 1 | 40 | 40 | 00 | 0 － | 55 |
| CLASS III |  |  |  |  |  |  |  |
| IHF－PAIIS FII PHASE | 1000 | 0 | 2－11 | 2411 | 40 | 90 | ， |
| WID－3ANT FII PHASE | 1209 | 0 | 230\％ | 386 | 0 | 00 | 9 |
| PULSE T－OTARRIUAL | 100 | 1 | 172 | $1{ }^{\text {² }}$ | リ－ | $1{ }^{1}$ | －604 |
| HOISE COPPELATIOH | 100 | 1 | 192 | 192 | $\stackrel{\square}{0}$ | 6 | 59 |
| DIRECTIDI FIHDEP | 701 | 0 | 1774 | 174 | 0 u | 00 | 5 |
| CLRSS IU |  |  |  |  |  |  |  |
| TPAFFIL LOOPS WPVSIDE FRDIO | 16 100 | 1 | 225 | 250 |  |  | －-75 |
| UFVSIJE FRDIO PHOTO\I－R DETECT | 109 30 | 1 | －20 | 2C0 | 93 40 | $0_{0}^{0}$ | －290 |
| PHOTONI－R DETECT ULTRHSOHIC DETECT | 30 20 | 1 | 08 | 63 | 45 | 00 | － 381 |

## VII．San Diego，CA，City AVM Cost Benefit Analysis Tables

Table 2－21．San Diego，CA，Gity AVM Physical Parameters

PFEM IS 531 SOUPFE IIILES．

LHET HEST DISTANCE IE 2S．s IIILES．

HOT TH GOUTH DISTINCE IS 41.2 IIILES．

TOTAL EOFII IIILEAGE I三 1945 IIILES．

THC IUUEER BF IHTEREECTIOH1S IS 13PGQ：

THE ESTITATEE IUNIEER GF ROAH SEGIENTS IS 2740G

THERE AFE SUG CRRS It THE FLEET

MI THEPE AFE ST MOTERCYCLES．

THE HU1BER OF UEHICLES ロH EACH SHIFT IS．

FIRST SHIFT IAPK．EE

FIFST SHIFT MIN EG

EECUND SHIFT IFAX． 95

ミ［GUMII SHIFT HITA． 95

THIRT SHIFT IAFX． 6

THIFII SHEFT I1IN．ES

THE CITY HWULJ PEQUIRE 23 WIDE－EAITD OR

FILSE T－D－H FITEItH SITES FHII 85 IARRPOI

SHIIS AIITEIMNF SITES HITH 7 AII 3 IILE COUERFGE RAIII．


NALBOW-gAND OR PULSE ANTENNA LCCATION -
Figure 2-11. San Diego, CA, AVM Pulse or Narrow-Band Antenna Locations

mde-zand antenna locatione
Figure 2-12. San Diego, CA, AVM Wide-Band Antenna Locations

Table 2－22．San Diego，CA，AVM Systems Cost Analyses

| $\begin{aligned} & \text { SFAN JIEGO } \\ & \text { CLASS } 1 \end{aligned}$ |  |  |  |  | totals |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | thouspios of s |  |  |  |  |  |  |
| －memimous | CHPS | SITES | JfSE | INSI | 0－11 | VuL | Sutic | Rabisor |
| 1 ETEOAPP | ＋1 | $\bigcirc$ | $\bigcirc$ | 31 | 105 | SU3 | 255 | 255 |
| STMLUS HAP | 705 | 0 | 39 | 21 | 108 | 1 1 ${ }^{\text {¢ }}$ | 982 | 23 |
| 2－ncceleponeters | 480 | 9 | 120 | 49 | 130 | 826 | 336 | 31 |
| LfESEP DELOCIMTR | 534 | 0 | 128 | 51 | 145 | 400 | TES | Y5u |
| UETPASOHIC UELO | 31 | ${ }^{4}$ | 129 | 4 | 145 | マヶ2 | 30 | $7^{78}$ |
| COTIPASSHOJOLIETER | 440 | 0 | 128 | 15 | 112 | T4， | 316 | 735 |
| COHPrSSS／LPSER UEL | 557 | － | 123 | 55 | 127 | 915 | 437 | ＋56 |
| CHPSSA－SOHIC UEL | 476 | 9 | 119 | 40 | 127 | 319 | 382 | 351 |
| Dilicga | 310 | 4 | 103 | 34 | 123 | 110 | 1203 | 1185 |
| LOPPII | 348 | 0 | 109 | 3. | 123 | 115 | 1233 | 1221 |
| decch | 3－5 | 0 | 149 | 28 | 123 | 653 | 720 | $7{ }^{-1}$ |
| ati－stations | 120 | 0 | 109 | 25 | 110 | 720 | tif | $\rightarrow 3$ |
| JIFF UTECG | 810 | 0 | 169 | 3.4 | 120 | $11{ }^{\text {c }}$ | 1101 | 1135 |
| DIFF LORFA | 840 | 0 | 169 | 3.4 | 153 | 115－1 | 1211 | 1231 |
| JIFF Ati－STA | 149 | 0 | 109 | 25 | 118 | 44 | ＋97 | 527 |
| RELHY OPEGA | 158 | － | 109 | 34 | 130 | $\xrightarrow{+}$ | －31 | 551 |
| FELM | 173 | 0 | 109 | 5. | 120 | －4． | 450 | 560 |
| CLIASIES KES LOOPS | 4e |  |  | 16793 | 105 | 26340 |  | 2832 |
| PEFLECTIMG SIGHS | $1-4$ | 3014 | 89 | 1693 | 339 | 5374 | 5400 | $53 ¢ 6$ |
| REFLECTILIE POAD | 33 | 929 | 59 | 2 but | 1749 | $\rightarrow 253$ | 4782 | 4205 |
| S－EALD POST | 51 | 3151 | 89 | 639 | 309 | 4205 | $\rightarrow 315$ | －03 |
| HF UHF POST | 47 | 34 | 89 | 17 | 155 | 657 | $3 \mathrm{C5}$ | G12 |
| LF FOST | 5 | 1713 | \％ | 640 | 310 | $28 \cdot 5$ | 283 | 2\％${ }^{\text {a }}$ |
| LIGHTSI－P POST | 4 | 1370 | 39 | 780 | $\rightarrow 50$ | 2738 | 2315 | 2709 |
| BURIED MAGHETS | 20 | 387 | 89 | 1997 | 109 | 3 ccs | 3279 | 32v2 |
| ULTEHSORIL POST | $-1$ | 2389 | 99 | 2355 | 29 | 5E55 | 5281 | Sius |
| TPAFFIC SEHCOF | 4 | 2003 | 09 | 1110 | 163 | duu5 | $43^{3} 3$ | 335 |
| CLRSS ITI 1 IRP－EATI FII PHASE | ${ }^{5}$ | 490 | 1－5 | ¢ | 150 | － | 1231 | $\cdots$ |
| WID－zHID FII PHASE | 0 | $30 \cdot 7$ | 176 | re | 219 | 1205 | 1023 | 160 |
| PULSE T－U－FPPRIUAL | 773 | 1199 | $35^{\circ}$ | 268 | 225 | 2812 | 2 C 3 | 2365 |
| NOISE COPRELATION | 236 | 29 | 357 | 4 | 13. | 398 | 925 | 332 |
| Dipectigh finder | 11 | so | 12 | 19 | 154 | $\rightarrow 1$ | 375 | 375 |
| TRaffic leops | 5 | 15559 | 39 | 3745 | 432 | 13850 | $1+040$ | 128－0 |
| Hat＇side radio | 4 | 13593 | 89 | 3119 | 7｀3 | 17011 | $1-6.1$ | 17011 |
| PHOTOMI－R DETECT | 令 | － 6 ？ | 29 | 1536 | $\rightarrow 4$ | 10917 | 1 V 717 | 10917 |
| ULTPRSOHIC detect | 33 | －94．4 | 89 | 1573 | 447 | 11655 | 11055 | 11 w 5 |

Table 2－23．San Diego，CA，AVM Polling Cycle Min／Max Times


| CLhss I TECHMITAE | TOTFL FLEET | STic | $\begin{aligned} & \text { SIIPPLE } \\ & \text { WOL } \end{aligned}$ | FPAM | 5 HC | SEEMTHARTT 0.01 | FAtD |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| IETEOPPD | 2773 | 14 du | 1078 | 2984 | 1989 | 1203 | 2267 |
| STYLUS I：HP |  | ${ }_{16}^{6}$ | $1{ }^{\circ} \mathrm{O}$ | 1316 | 688 | 5 12 98 | 14.32 |
| ORLUS fin |  | 572 | －${ }^{1}$ | 13 | $7 \%$ | $\bigcirc$ | 14 \％ |
| 2－mCCELEf OIIETEPS | \％ 49 | 1530 | 1090 | 2103 | 1127 | 1241 | 23.65 |
|  |  | 550 | 042 | 12.28 | $\cdots$ | 7 cm | 1．So |
| Lficer jelocinit | ＊ 35 | 1551 | 11 U3 | 21.15 | 1150 | 1267 | 23 31 |
| LLTFHSOHIC MELO | $\approx 49$ | 16.89 | ${ }_{10}^{764}$ | 13.10 |  | $\square$ 1200 41 | 1475 |
|  |  | $\bigcirc 56$ | －浣 | 13 | $5+12$ | 73. | $1+50$ |
| COM1PHSSOSOIOHETEF | $34^{4}$ | $1{ }^{10} 3$ | 1096 | 21 9\％ | 1127 | 1241 | 2305 |
| COHPMSS／LASEP UEL | 3849 | ${ }_{10}^{65}$ | $10^{\circ}{ }^{4}$ |  | ${ }_{1 i} 12$ | 784 18 4 | 1．56 |
|  |  | 550 | $\bigcirc{ }^{0}$ | 13 | 7.12 | 78 | $1+50$ |
| CIPSSATSOHIC UEL | 3 49 | 1039 | 1046 | 21.03 | 1127 | 1241 | 2305 |
|  |  | 650 | $\bigcirc{ }^{-2}$ | 13 ck | 712 | 78 | 1．50 |
| Ofegh | 7154 | 1121 | 1188 | ${ }_{1} 185$ | 129 | 14.06 | 2476 |
|  |  |  | ${ }^{7}$ | 1389 | ${ }^{3} 16$ | \％ 89 | 15 25 33 |
| LOFfti | 4271 | 1153 | $1{ }^{1} 10$ | $\begin{array}{ll}22 & 17 \\ 14 & 69\end{array}$ | 1355 856 | 14.89 | 25 168 |
| DECCH | －2 2 | 11.40 | 119 | 2204 | 1330 | $1 .+$ | 2598 |
|  |  | ？ 29 | 755 | 1392 | 840 | 912 | 1584 |
| MIT－STHTIOHES | 330 | 1428 | 1083 | 2998 | 1108 | 1215 | 2230 |
|  |  | ¢ 3 | 68 | 13.80 | 59 | $\bigcirc$ | 14， |
| DIFF Wlech | $+154$ | 1131 | 11.9 | 2185 | 1292 | 14 Ab | $2{ }^{2} 7$ |
| diff Loppai | ＋271 | 1153 | 1215 | 2217 | － 10 | 14838 | 155 |
|  |  | 7 \％ | $7{ }^{7}$ | 1－60 | 85 | 928 | 16 ¢ |
| Jiff R6I－STA | －130 | 1115 | 1172 | 2179 | 127 | 1393 | 2457 |
|  |  | 76 | 740 | 1370 | 803 | 380 | 1552 |
| PELAY OTEGA | 355560 | 95959 | 96897 | 97914 | 199950 | 191064 | 192128 |
|  |  | 60690 +117 | ${ }^{606} 56$ | 01272 | 129600 | 12967 | 1213 4it |
| FELH LOFPM | 15253 | $\begin{array}{ll}41 & 17 \\ 20 & 00\end{array}$ | $\begin{array}{ll}41 & 74 \\ 20 & 36\end{array}$ | 5181 | 7283 | 73 467 46 | 8461 534 |
| Class II EURIED FES LOOPS | 3872 | 10.45 | 2636 1102 | 3272 2109 | 4609 11.0 | 4675 | 5344 2318 |
|  |  | 6 ¢ | 59 | 133 | 720 | 73 | 14.64 |
| REFLECTING SIGHS | 3872 | 1945 | 1102 | 2109 | 1140 | 125. | 2318 |
|  |  |  |  |  |  | 7.92 1254 | 14.64 |
| FEFLECTIAG ROAB | 38 | 1085 680 | 11 1180 0 |  | $1159$ | 1254 7.48 | 23 10.6 |
| ＜－Ertid Post | $\checkmark 4$ | 1439 | 10 90 | 2183 | 1127 | 124 | 23.45 |
|  |  | Cos | ${ }^{\circ} 9$ | 1328 | ？ 12 | 7－8＊ | 1450 |
|  |  | 10.26 | 1933 |  | 1182 | 12 t | 22808 |
| LF POST | 484 | 1039 | 149 | 2103 | 118 | 124 | 14.40 |
|  |  | $0^{5}$ | 59 | 1323 | 712 | 78 | 1450 |
| LIGHT／I－P FOST | 3849 | 1039 | 1690 | 2103 | 1127 | 1241 | es es |
|  |  |  | 692 | $13-8$ | 714 | 78 | 1450 |
| Fiples mfichets | 3872 | 1045 | 11 v2 | 2169 | 1149 | 1254 | 213 |
|  |  | E 80 | $1{ }^{5}$ | 1332 | 7.29 | 732 | 1484 |
| HITHASOHIC POST | 3849 | 1439 | $100^{\circ}$ | 2105 | 1127 | 124 | 2305 |
|  |  | 650 | $0{ }^{\circ} 9$ | 1328 | $\overline{7} 12$ | 734 | 1.50 |
| truffic sertiop | 3849 | 1039 | 10.0 | 21.83 | 1127 | 12 ${ }^{1}$ | 2305 |

Table 2－24．San Diego，CA，AVM Accuracies and Cost Benefits with One Radio Channel

| STSEIT HCCUPACIES（H），UEHICLES AMD |  |  |  | ES AHD | $\begin{gathered} \text { ESTII } \\ \text { UEHI } \\ \text { OS } \end{gathered}$ | 5 51000 | SmuItics ESTILHATES ᄃ－ 5 EHF |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| TECHMIOUE HCCL | PAC | SRUE3 | Itas | IIN | $1 \mathrm{H}_{6}$ | IIN | SMIJHC |
| －EVEORRD | 3 | 0 | З3ご | 245 | 23 | 24 | 1,55 |
| Stilus tife | － | 6 | －-5 | $2 \mathrm{S3}$ | 27 | 2こ | 1．35 |
| 3－hCOELEFOSIETEFS | 3 | 0 | 383 | 349 | 28 | を3 | 1－ら゙1 |
| LISEFP UELOCIIITP | 1 | 7 | 331 | － | $\pm 6$ | 3 | 15゙5 |
| U TPASDHIL VELO | － | $\checkmark$ | 300 | 259 | 28 | 20 | $1 \sim 5$ |
| COHPASS－ODO12 | Cl | E | 32 |  | 23 | $\stackrel{\square}{4}$ | ！ |
| COHPAJごLASER VEL | 15 | L | 30 | С－3 | ¢ 8 | こ | 1－t5 |
| Etipssulu－S03IC UEL | $1-$ | 6 | 300 | 244 | 23 | 24 | 195050 |
| 0iliga | 1erus | U | ＋18 | $\rightarrow 112$ | 40 | 0.4 | 1 |
| Lupati | 10 | 5 | $4+3$ | 412 | 1.9 | 17 | こ1u |
| JECCA | 200 | － | 50 r | －9E | 14 | 10 | ヶ30 |
| AT1～シTATIOHS | 20¢ | 4 | 59 | 29.4 | 17 | 10 | тur |
| JIFF UIECA | 104 | 5 | $-17$ | 411 | 1 a | 2 | 35 |
| JIFF LUFH1 | 405 | $\checkmark$ | 1107 | 1142 | 40 | 49 | 13 |
| JIFF HII－STG | 253 | 4 | 015 | 59＊ | 4 | 4 b | 13 |
| RELAS UIIEGA | 509 | 1 | 3369 | 26369 | 45 | 00 | $\underline{1}$ |
| PELFIT LOPM | 605 | 3 | －1，3 | $23+3$ | vo | 06 | $v$ |
| CLHES ii |  |  |  |  |  |  |  |
| YURIE PES LOQP3 | 10 | － | 375 | 241 | 23 | 24 | 155 |
| REFLECTING SIGNS | 10 | 2 | 367 | $2 \rightarrow 1$ | ¢ 8 | 27 | Ctus |
| PCFLECTINC POHJ | 3 | － | 30．\％ | 233 | 29 | 26 | －5－0 |
| －3prey poit | 12 | $\checkmark$ | 37 | 241 | L 3 | 24 | 555 |
| HF，DHF POST | 15 | 6 | $3 ゙ 5$ | 240 | $\leq 8$ | 2 | リ．c゙3 |
| LF Posi | 15 | 6 | 489 | 273 | $\therefore 0$ | く2 | 140 |
| LIGHT／I－F POST | $\because$ | D | $30^{2}$ | 23 | 23 | 25 | －159 |
| UUFIES LIMENETS | 4 | ， | $3{ }^{-}$ | 235 | 2 | $\sim 5$ | 1060 |
| ULTPASOHLC POST | 20 | 5 | 382 | $2 \cdot 5$ | 28 | ¢ 4 | 14 |
| TFHFF IC SENSOP | 10 | 7 | 375 | $2 \rightarrow 9$ | 28 | 25 | 1 ず |
| CLfOS III |  |  |  |  |  |  |  |
| H1F－EMIT FIL PHBSE | Iftus | 4 | 30.0 | 2639 | 96 | 15 | ${ }^{4}$ |
| UiJ－2ath fit Phase | 1200 | 4 | 315 | 3196 | 00 | 4 L | 4 |
| PULEE T－0－nEPILAL | 1 vo | c | 191 | 137 | 31 | － 5 | 2254 |
| HOIGE CDFPELATIOH | 100 | $\bigcirc$ | 214 | 2u9 | 3 | 4 | －230 |
| SIFECTIDA Fitjep | －00 | U | 1970 | 1435 | 90 | 00 | U |
| CLhjs if |  |  |  |  |  |  |  |
| TFHFFIC LOOPS | 10 | 7 | 20 | 23 | 40 | $\cdots$ | 20x |
| Hascije padio | 100 | 0 | 203 | 207 | 3 | 4. | 5 |
| PHDTOSI－R JETECT | 20 | 6 | 59 | 00 | 38 | 57 | －1919 |
| UTTREOHLC JETECT | CO | $\bigcirc$ | 72 | $\rightarrow 3$ | 3 3 | 11 | cごo |

Table 2－25．San Diego，CA，AVM Accuracies and Cost Benefits with Two Radio Channels

| 3H1 JIEGO | Sistenf | CCUPACIES | In ，UEHICLES AtID SMSTEII |  | ESTIHRTED EIUU UEHICLES |  | SAUINGS ESTIIfATED |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| CLHSS I ULT | tate | UEHICLES |  | AC |  |  |  |
| TECHEITUUE ACCL | SC＇\％ | SAlUED | MÅ | MIH | MAY | IIII | SRIMİG |
| FE，EOARD | 33 | － | 123 | 95 | 3 E | 52 | 5375 |
| STYLUS MAP | 30 | E | 153 | ช2 | 37 | 51 | 32\％ |
| 2－RCCELEPOIETEPS | 34 | － | 130 | $\infty$ | 36 | 52 | 3550 |
| LfsER UELOCIHTR | 13 | 7 | 130 | 50 | 2 | 5.2 |  |
| ULTEHSOHIC IELO | $\sim 9$ | 6 | 131 | 103 | 35 | 51 | S1us |
| CAIPASSRODOMETEP | 29 | 6 | 120 | 80 | 57 | 52 |  |
| COAPASSMASER JEL | 15 | 0 | 120 | $\rightarrow$ | 37 | 52 | 2005 |
| CIPSSA－SCHIC JEL | 17 | 6 | 12 \％ | $7{ }^{7}$ | 37 | 52 | 3205 |
| 0 OEGA | 16и4 | 0 | －勹¢ | 3 ycz | $0 \cdot 9$ | 0 b | 4 |
| LOPAt | 100 | 5 | 401 | 393 | 26 | 22 | 14＊5 |
| DECCA | 2050 | $\rightarrow$ | 483 | $\rightarrow 7$ | 15 | 13 | 510 |
| Ati－STATIDIS | 2บ | 4 | 481 | 472 | 15 | 13 | 535 |
| SIFF gliche | 160 | 5 | －90 | 393 | 2．u | ご | 1055 |
| DIFF LURPI | 400 | 2 | 1109 | 11405 | 00 | 0 ¢ | 0 |
| DIFF RII－STA | 253 | $\rightarrow$ | 581 | 570 | 1.0 | 03 | 160 |
| RELFI OHEGA | 500 | 11 | 16934 | 6592 | 00 | 00 | 0 |
| PELA，LOPAH | 309 | 0 | 2276 | 2®21 | 06 | 9 | 4 |
| Class il |  |  |  |  |  |  |  |
| JURIES PES LOOPS | 11 | 7 | 120 | $7^{\text {a }}$ | $\bigcirc 7$ | 52 | 2373 |
| PEFLECTLIG SICNS | 19 | $\overline{7}$ | 120 | $7{ }^{9}$ | \％ | 52 | 2000 |
| PEFLECTIHC ROAJ | 3 | 7 | 122 | 7 | 3 | 53 | －779 |
| $x-38 N 2$ POST | 12 | 7 | 126 | 72 | 37 | 52 | 2355 |
| HF：VHF POST | 15 | 2 | 120 | 78 | 37 | 52 | －125 |
| LF POST | 109 | 6 | 265 | 259 | 27 | 57 | 12 5 |
| LICHT－I－P POST | $\geqslant 0$ | 0 | 130 | 31 | 3 | 52 | 115 |
| BUPIES Hagineis | ＋ | 7 | 123 | 77 | 37 | 52 | $\checkmark 400$ |
| ULTPASOHIC POST | 20 | 6 | 123 | 80 | 37 | 52 | $1 \geqslant+15$ |
| TIHFFIC SEHSOR | 10 | 7 | 126 | ${ }^{7} 8$ | 36 | 52 | 305 |
| CLASS III |  |  |  |  |  |  |  |
| HMF－EATHI FH PHASE | 1000 | 0 | 2550 | 2494 | 60 | 90 | $u$ |
| WIう－JPHD FH PHASE | 1200 | 0 | $3 \cup 24$ | 2Yod | U．13 | 09 | 0 |
| PULSE T－D－APRIUGL | 190 | $\bigcirc$ | 191 | $1 \mathrm{C7}$ | 31 | $\cdots$ | くでu |
| IGISE COPRELATIOH | 109 | 0 | 214 | 209 | 3.5 | 4 | E2れ |
| gircctioh fillity | － 0 | 0 | 1870 | 1005 | 40 | 50 | $v$ |
| CLASS Il |  |  |  |  |  |  |  |
| TPaffic luops | 10 | $\checkmark$ | こう | 23 | $\rightarrow 0$ | 63 | \％ |
| WASSIDE PADIO | 150 | $\bigcirc$ | 203 | 207 | 20 | $\because$ | L－63 |
| PHOTO I－F DETECT | 6 | 6 | 59 | Bd | 3 | 59 | －194 |
| ULTRASOHIC DETECT | E0 | $\cdots$ | 42 | $\rightarrow 3$ | こ | E 1 | 2 |

VIII．Los Angeles，CA，City AVM Cost Benefit Analysis Tables

Table 2－26．Los Angeles，CA，Central Bureau AVM Physzcal Parameters

HFEH I＇ 5 － 5 OOUPPE HILE
EHST HEST IIETAHCE IS 9 HILES．
HORTH SOUTH DISTFHEE IS 1F MILES．
TOTfL FGFI MILEEGE I 115 É HILE
THE HUNLEFF OF IUTEF EENTIOLAG IS 9570．

THIFE HPE 157 GAFS IN THE FLEET．
FII THEFE AFE G HOTORCGLES．
THE HUIBEF OF リEHICLEE OH EFCH EHIFT IS：
FIFET BHIFT HH：．EG

「IFET EHIFT MIH．59

AECOIJ SHIFT HF゙ッ G

SECOHI SHIFT MIH．EG

THIFT EHITT MA，106

THIEI SHIFT HILA．

THE IHJIEEF OF HIEFATEHEF

THE EIT，HOULII kEOUIFE E HINE＋EFIIII OF



Table 2－27．Los Angles，CA，Central Bureau AVM Systems Cost Analyses

| Lfi－CESTRRAL BJREAU CLASS 1 |  |  |  |  |  | TOTALS |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| techilious | CRRS | THut | THuIISAIIDS OF | INST | 0－11 | Unt |  | FPMDO： 1 |
| KEY BAFR】 | 22 | ${ }^{4}$ | $7{ }^{7}$ | 16 | 103 | 237 | 210 | 212 |
| STYLUS MAP | 401 | 9 | 72 | 16 | 164 | 617 | 593 | 592 |
| 2－ACCELEPOHETEPS | 252 | 0 | 105 | 26 | 116 | 513 | 549 | 541 |
| LHSER UELOCIMTR | 280 | 9 | 109 | 32 | 124 | 568 | 599 | 591 |
| ULTRRSONIC VELO | 200 | 4 | 195 | 26 | 124 | 483 | 513 | 505 |
| COLPASS／ODOLIETEP | 231 | 0 | 105 | 14 | 197 | 483 | 521 | 565 |
| COMPRSS／LASER JEL | 292 | $\underline{\square}$ | 119 | 34 | 115 | 573 | blv | 594 |
| CHPSSA－SOHIC UEL | 249 | 6 | 100 | 26 | 115 | 520 | 553 | 542 |
| Oricgs | 424 | 4 | 92 | 23 | 112 | D70 | 717 | 708 |
| LORAM | 440 | 6 | 9 | 23 | 112 | 092 | 733 | 727 |
| jeccis | 151 | 4 | 93 | \％a | 112 | 429 | 471 | 403 |
| BM－STAT IONE | 03 | 6 | 93 | 18 | 116 | 303 | 338 | 330 |
| DIFF OHEGA | 424 | 0 | 98 | ze | 112 | 676 | 706 | 708 |
| DIFF．LOPPI | $\rightarrow 48$ | 9 | 92 | 20 | 112 | 698 | 721 | 727 |
| DIFF．HM－STA． | 4 | 0 | 交 | 13 | 119 | －18 | $3+8$ | 363 |
| RELAY OHEGG | 63 | 0 | 93 | 23 | 116 | 33 | 313 | 376 |
| RELAY LUFFIH | 91 | 0 | 72 | 23 | 116 | 246 | 321 | 38.4 |
| CLRSS 11 |  |  |  |  |  |  |  |  |
| EURIED RES，LOOPS | 22 | 6891 | 泡 | 11731 | 103 | 188.43 | 18858 | 18812 |
| REFLECTING SIGNS | 76 | 2186 | 72 | 1182 | 295 | 3755 | 3770 | 3730 |
| REFLECTING PCAD | 29 | 230 | 72 | 1398 | 1251 | 2995 | 3010 | 2970 |
| S－BAND PAST | 27 | 2202 | 72 | 447 | 2.45 | 3017 | 2032 | 2992 |
| HE，UHF POST | 25 | 249 | 72 | 124 | 138 | 623 | 638 | 597 |
| LF POST | 24 | 1197 | 72 | $4+8$ | 246 | 2911 | 2026 | 1956 |
| LIGHT／I－R POST | 23 | 957 | 72 | $5 \cdot 9$ | 34.4 | 1969 | 1984 | $19+4$ |
| PURIED MRCNETS | 16 | 690 | 72 | 1396 | 190 | 2298 | 2312 | 2272 |
| ULTRASONIC POST | 22 | 1627 | 72 | 1651 | 296 | 3691 | 3700 | 366E |
| TRAFFIC SEliSOR | 23 | 1819 | 72 | 782 | 102 | 2822 | 2337 | 279 |
| CLASS III |  |  |  |  |  |  |  |  |
| NSR－BAHD FM PHASE | 36 | 66 | 142 | 22 | 111 | 376 | 415 | 419 |
| WID－BAND Fli Phase | 457 | 24 | 135 | 23 | 205 | 87 | 883 | 390 |
| PU．SE T－O－RRRIUAL | 405 | 190 | 332 | 69 | 186 | 1187 | 1226 | 1230 |
| NOISE CORRELATION | 12.4 | 29 | 332 | 31 | 181 | 720 | 734 | 738 |
| DIRECTIGN FINDER | 6 | 79 | 78 | 17 | 154 | 352 | 333 | 333 |
| CLHSS IU |  |  |  |  |  |  |  |  |
| TRAFFIC LOOPS | 13 | 9890 | 72 | 2615 | 332 | 12922 | 12922 | 12922 |
| WRYSIDE RADIO， | 12 | 8608 | 72 | 2139 | 531 | 11451 | 11451 | 11451 |
| PHOTOM I－R VETECT | 19 | 5497 | 72 | 1103 | $3-42$ | 7031 | 2031 | 7031 |
| URTRASONIC DETECT | 20 | 5592 | 72 | 1102 | 342 | 7127 | 2127 | 7127 |

Table 2－28．Los Angeles，CA，Central Bureau AVM Polling Cycle Times

CYCLE TIHE IN SECONDS TO POLL MFX GHD MIN UHITS DEPLOYED

| CLASS I <br> TECHHIOUE | TOTPL fleet | STHC | SIIPLE | Ramb | SYHC | PESUHDPAT vor 12.5 | RFit |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| KEYPCFRD | 1085 | 1073 | 1127 | 2189 | 11.47 |  | 2580 |
|  | 17.53 | $\begin{array}{r}5 \\ 11 \\ \hline 18\end{array}$ | $\begin{array}{r}5 \\ 11 \\ \hline 83\end{array}$ | 18 229 98 | 1243 | $\begin{array}{r}627 \\ 13 \\ \hline 67\end{array}$ | 11180 |
| Stilus fer | 17．38 | 569 | 587 | 1113 | 6.29 | 673 | 1278 |
| 2－fCCELEROMETERS | 1717 | 10.93 | 1147 | 2200 | 11.87 | 1243 | 2409 |
|  |  | 547 | 573 | 1100 | 593 | 647 | 128 |
| Lrser velocimir | 1733 | 11.07 | 11.60 | 22.13 | 1213 | 13 |  |
| ULTRASONIC MELO | 1717 | 553 1893 | 588 11 47 | 2¢ 11.07 | － $11-97$ | 1203 | 12468 |
| Uldisoric yalo |  | 547 | 573 | 11．00 | 593 | 647 | 1208 |
| COMPRSS O－ODCTETER | 17.17 | 1693 | 1147 | 2209 | 1187 | 12 \＄3 | 2490 |
|  |  | 5 19 19 | 11．73 | 118 | 593 1187 | 647 1293 | 1200 |
| COMPRSS／LASER UCL | 1717 | 1093 59 | 11.47 | ${ }_{11} 2208$ | 11 597 | 1293 <br> 6 <br> 7 |  |
| CIPSSA－SOHIC VEL | 1717 | 1093 | 1147 | 2280 | 1187 | $1 \times$ | 2400 |
|  |  | 577 | 573 | 1140 | 593 | 647 | 12 eq |
| OTEGA | 1853 | 118 | 1233 | 2287 | 1360 | 14.67 | 2573 |
| LORPat | 1905 | 1213 | 1267 | 20 20 | 1487 | $15 \stackrel{3}{3}$ | 2040 |
|  |  | 6 Ca | a 33 | 11.68 | 713 | 767 | 1320 |
| DECCR | 1884 | 1298 | 1253 | 2387 | 1480 | 1567 | 2613 |
|  |  | 0.96 | 027 | 1153 | 708 | 753 | 1307 |
| AMT－STATIORS | 1690 | 108 | 1133 | 2187 | 1160 | 1267 | 2373 |
|  |  | 548 | 567 | 1993 | $5 \%$ | 633 | 11.87 |
| DIFF OTEGA | 1853 | 1180 | 1233 | 22 87 | 1360 | 1487 | 2573 |
|  |  | 590 | 617 | 11.43 | 680 | 733 | 1237 |
| Diff Lorft | 1985 | 1213 | 12 b | 2320 | 1427 | 1533 | 204 |
|  |  | 695 | － 37 | 11 － | 713 | 767 | 1320 |
| DIFF Pri－STA | 1842 | 11 7 | 1227 | $12 \%$ | 1347 | 14 7 7 | 2560 1234 |
| RELAY OMECA | 150570 | $1010{ }^{5} 07$ | 1419 | 11 102108 | 673 291800 | $\begin{array}{rl}7 \\ 2911 & 27 \\ 67\end{array}$ | rese 123 |
|  |  | 5056 | 50527 | 51053 | 100509 | 180553 | 1011 6？ |
| RELAY LORAN | 6303 | 4333 | 4387 | 5448 | 76．07 | 7773 | 83 \％ |
|  |  | 2167 | 2193 | 2720 | 3833 | $38 \pm 7$ | 4440 |
| EAPIED RES LOOPS | 1727 | 11 505 50 | 11 5 57 | 2e 07 11.03 | 1209 0604 | 13 507 50 | 24.13 |
| Reflectinit sighis | 17 ar | 118 | 1153 | 2807 | 12 OH | 1307 | 2413 |
|  |  | 550 | 57 | 1183 | ${ }_{6} 89$ | ${ }^{6} 53$ | 1207 |
| feflecting road | 1727 | 1180 | 1153 | 2207 | 12 E | 136 | 2413 |
|  |  | ${ }_{16} 59$ | 5.77 11.47 | 11.63 | ${ }_{11}^{6} \mathrm{LB}$ | ［6938 | 12 2469 |
| X－EATi POST | 1717 | 1093 547 | 11.47 5 73 | 11 11 11 00 | 1187 593 | 1293 $0+4$ | 24 12909 |
| HF，MHF POST | 16． 90 | 1089 | 11.33 | 2187 | 1160 | 1267 | 2373 |
| LF POST | 1717 | 5 1093 | 511 11 48 | 1993 | 11\％ 88 | 1633 | 118 |
| LF POST | 1.17 | 547 | 573 | 1160 | 593 | 047 | 1260 |
| LIEAT／I－R POST | 17．17 | 1093 | 11.7 | 2289 | 1187 | 1293 | 2400 |
|  |  | 547 | 573 | 1180 | 593 | 647 | 1200 |
| StRIED IfPGETS | 15－27 | 110 | 1153 | 2207 | 1290 | 1307 | 24.13 |
|  |  | 550 | 57 | 1103 | 649 | 65 | 1207 |
| LLTRASOHIC POST | 17.17 | 1893 | 1147 | 2200 | 11.87 | 1293 | 2400 |
|  |  | 5．${ }^{\text {＋}}$ | 5 11 7 | 1100 | 593 11.87 | $\begin{aligned} & 087 \\ & 124 \end{aligned}$ | $\begin{aligned} & 1200 \\ & 2400 \end{aligned}$ |
| TPAFFIC SEHSOR | 178 | 10，${ }_{5}$ | $\begin{array}{r} 11 \\ 573 \end{array}$ | 1109 | ＋11＊88 | $\begin{array}{r} 1293 \\ 647 \end{array}$ | $\begin{aligned} & 2400 \\ & 1209 \end{aligned}$ |
| 7 |  |  |  |  |  |  |  |

Table 2-30, Los Angeles, CA, Central Bureau AVM Accuracies and Cost Benefits with Two Radio Channels



Figure 2-13. Los Angeles, CA, AVM Pulse or Narrow-Band Antennas

Table 2-31. Los Angeles, CA, Central Bureau AVM Accuracies and Cost Benefits with Three Radio Channels



Figure 2-14. Los Angeles, CA, AVM
Wide-Band Antenna Locations

Table 2－32．Los Angeles，South Bureau AVM Physical Parameters

FPEA IS 55．E SOUAPE HILES．
EFST WEST IISTANCE IS 9 IIILES．
HORTH SOUTH DISTANLE IS ES MILES．
TOTAL ROAD IIILEAGE IS 973 IIILES．
THE INNIBER OF INTERSEETIOIS IS 6090.
THE ESTIMATED NUHEER OF ROAD SEGHEIITS IS IE1G日：
THERE RFE 165 CAPS IN THE FLEET．
AHD THEFE RRE G HOTOPCYCLES．
THE INUIBER OF UEHICLES OH EFCH SHIFT IS：
FIFST SHIFT HAN．63

FIFET SHIFT 11IH． 53

SECOMI SHIFT HFFR．G4

SECOHLUSHIFT HIH． $\mathbf{5 4}$

THIFI SHIFT IAKA．104

THIRI SHIFT HIIN． 94

THE HUHEEF OF IISFRTCHEFS IS 2

THE EITY HOULI REOUIRE 5 UILE＋BRND OR
FIULSE FHTEINA SITES AIHE 2з HARROW BAIID
FII RITEENHF SITEG FOF 7 RIII 3 IIILE RHIIUS COJEFFGE．

Table 2－33．Los Angeles，South Bureau AVM Systems Cost Analyses

| LA－SBUTH EURERU CLASS I |  |  |  |  |  | TuTALC |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| TECHILOUE | CRPS | THOUSPADS 0 Of |  | E ItST | 0－11 | 402 | SYTM | Fhndicil |
| KEYEORRD | 23 | SIES | 73 | 16 | 103 | 2－${ }^{\text {a }}$ | $\geq 14$ | 214 |
| STRLUS MAP | 421 | ${ }^{4}$ | 73 | 10 | 105 | 041 | 614 | 014 |
| 2－ACCELEROMETERS | 264 | 6 | 140 | 27 | 117 | 504 | 568 | 558 |
| LASEP UELOCIMTR | 294 | U | $10^{\circ}$ | 33 | 125 | 556 | 519 | D11 |
| ULTRASOMIC JELO | 216 | 0 | 109 | 27 | 125 | ，$\square^{7}$ | 529 | 521 |
| COMPASS OODOMETER | 242 | $\theta$ | 149 | 14 | 107 | 498 | $53^{\circ}$ | S2品 |
| COMPASS／LFISER VEL | 367 | 6 | 149 | 35 | 115 | 592 | 6.31 | 617 |
| CTIPSS／I－SONIC VEL | 262 | 0 | 107 | 27 | 115 | 537 | 570 | 559 |
| OMECA | $\rightarrow 4{ }^{4}$ | 0 | 93 | 24 | 113 | 731 | 745 | 834 |
| LORRH | $\rightarrow$－ | － | 93 | 24 | 113 | 717 | 701 | 75. |
| IECCA | 190 | 0 | 93 | 20 | 113 | $\rightarrow+$ 20 | 480 | 477 |
| PM－STATIONS | 60 | 0 | 93 | 19 | 110 | 214 | 3.5 | Эち3 |
| DIFF．DMEGR | 446 | 0 | 93 | 24 | 113 | 761 | 73 | 734 |
| DIFF LORAN | 462 | 0 | 93 | 24 | 113 | 717 | 749 | 754 |
| DIFF．AMI－STR | 77 | 0 | 93 | 19 | 114 | 205 | 356 | 375 |
| RELAY OHEGA | 97 | 0 | 93 | $2 \cdot 4$ | 117 | 340 | 320 | 336 |
| RELPY LORPN | 95 | 0 | 93 | 2 | 117 | 354 | 328 | 374 |
| CLASS II |  |  |  |  |  |  |  |  |
| BURIED RES LOGPS | 24 | 4093 | 73 | 6975 | 163 | 11293 | 11308 | 11266 |
| REFLECTING SIGHS | 80 | 1340 | 73 | 760 | 226 | 2516 | 2525 | 2483 |
| REFLECTING RORD | 21 | 147 | 73 | 897 | 834 | 1977 | 2012 | 1970 |
| X－ERHD POST | 29 | 1491 | 73 | 291 | 193 | 2012 | 2028 | 1936 |
| HF，MMS POST | 26 | 153 | 73 | 86 | 125 | 487 | 503 | 461 |
| LF PGST | 25 | 762 | 73 | 292 | 194 | 1371 | 1387 | 1345 |
| LIGHT／I－R POST | 24 | 609 | 73 | 358 | 257 | $13+7$ | 1362 | 1320 |
| EURIED MAGNETS | 17 | 416 | 73 | 536 | 106 | $1+62$ | 1477 | 1435 |
| ULTRASONIC POST | 23 | 1936 | 73 | 1660 | 226 | 2443 | 2453 | 2416 |
| ＇TRAFFIC SENSOP | 24 | 1158 | 73 | 504 | 102 | 1836 | 1992 | 1860 |
| CLASS 111 |  |  |  |  |  |  |  |  |
| NAR－BANY FII PHHSE | S6 | 109 | 143 | 27 | 116 | 431 | 472 | 476 |
| WID－BAND FIT PMRSE | 486 | 58 | 134 | 33 | 207 | 911 | 954 | 956 |
| PULSE T－O－ARRIUPL | 425 | 322 | 331 | 93 | 191 | 1361 | 1462 | 1447 |
| NOISE CORRELATICH | 136 | 29 | 331 | 31 | 181 | 726 | 742 | 747 |
| direction finder | 6 | 79 | 78 | 17 | 154 | 353 | 334 | 334 |
| CLASS IU TRAFFIC LOOPS | 14 | 4823 | 73 | 1673 | 248 | 6829 | 6829 | 6829 |
| Wfisile radio | 13 | 4135 | 73 | 1393 | 407 | 6019 | 6019 | 6019 |
| PHOTOSI－R DETEG | 19 | 3548 | 73 | 710 | 255 | 3605 | 3695 | 3605 |
| ULTRASONIC DETECT | 21 | 2689 | 73 | 709 | 255 | 3667 | 3667 | 3667 |

Table 2－34．Los Angeles，South Bureau AVM Polling Cycle Times

CTCLE TIFE IN SECONDS TO POLL MRX FAD HIM UNITS DEPLOYED


Table 2－35．Los Angeles，South Bureau AVM Accuracies and Cost Benefits with One Radio Channel


Table 2-36. Los Angeles, South Bureau AVM Accuracies and Cost Benefits with Two Radıo Channels

LA-SOUTH ZURERU


Table 2-38. Los Angeles, West Bureau AVM Physical Parameters

HFEA IS 155. G SOUAFE MILES.
EFET HEST TISTATICE IS 19 hiles.
HOPTH SDUTH IISTRILE IS 13 miles.
TUTAL FOFID HILEAGE Is 1677 hiles.
THE HUHEER OF IHTEFSECTIONS IS 3401.
the estimated humber of poid segithts is 1ejog:
THEFE RRE 193 CARS IH THE FLEET.
frim there fre a hotopcycles.
the hulteef of vehicles din each shift is:

## TIFET SHIFT MAK.. 59

TIFST SHIFT HIH. 3 ?

SECOHD SHIFT MAM. 105

EECOHZ SHIFT MIH. 94

THIFI SHIFT MFV. 117

THIFO EHIFT HIH. 95

THE HUIEEF OF DISPATCHEPS IS a
THE CIT / HOULD REGUIRE 7 HIDE EFHH OF



Table 2-39. Los Angeles, West Bureau AVM Systems Cost Analyses


| LA-HEST RURERU <br> CLASS I |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | TRGU | AnS Of |  |  |  |  |  |
| TECHILQUE | CARS | SITES | ERSE | IHST | 0-1 | VOL | SYHC | RENDCM |
| KEYBOARD | 25 | 0 | 78 | 17 | 103 | 252 | 222 | 222 |
| STYLUS MRP | 467 | 0 | 78 | 17 | 195 | 695 | 666 | 666 |
| 2-ACCELEROMETERS | 293 | 0 | 111 | 29 | 119 | 580 | 616 | 607 |
| LRSER UEILOCIMTR | 326 | 0 | 116 | 35 | 128 | 634 | 679 | 661 |
| ULTRASONIC UELO | 233 | $\square$ | 116 | 29 | 128 | 534 | 578 | 561 |
| COMPRSS/ODOMETER | 269 | 0 | 116 | 14 | 108 | 535 | 579 | 56 |
| COMPRSS/LASEP VEL | 348 | 9 | 116 | 38 | 117 | 639 | 683 | 664 |
| CIPSS/U-SONIC UEL | 291 | 0 | 110 | 29 | 117 | 575 | 619 | 605 |
| OMEGA | 495 | 0 | 98 | 25 | 11. | 70 | 869 | -97 |
| LORRN | 513 | 0 | 98 | 25 | 114 | 779 | 827 | 819 |
| DECCA | 211 | 0 | 93 | 21 | 11. | 473 | 521 | 512 |
| FAT-STATIONS | 74 | 0 | 98 | 20 | 111 | 331 | 366 | 357 |
| DIFF OHECA | 495 | $a$ | 98 | 25 | 114 | 760 | 795 | 797 |
| DIFF. LORAN | 513 | 0 | 9 | 25 | 114 | 779 | 813 | 314 |
| DIFF. AM-STA. | 86 | 0 | 98 | 20 | 111 | 343 | 378 | 390 |
| RELAY OMEGF | 97 | 0 | 93 | 25 | 119 | 367 | 338 | 411 |
| RELPY LORPA | 186 | 0 | 98 | 25 | 119 | 376 | 347 | 429 |
| CLRSS II |  |  |  |  |  |  |  |  |
| BGRIED RES LOOPS | 25 | 6768 | 78 | 11524 | 103 | 18588 | 18545 | 18499 |
| REFLECTIMS SIENS | 88 | 2068 | 78 | 1166 | 203 | 3721 | 3738 | 3091 |
| REFLECTING RORD | 23 | 226 | 78 | 1375 | 1231 | 29s3 | 2979 | 2932 |
| X-BRND POST | 32 | 2162 | 78 | 441 | 243 | 2984 | 3091 | 2955 |
| HF, UHF POST | 29 | 235 | 73 | 124 | 138 | 631 | 649 | 662 |
| 15 POST | 28 | 1175 | 78 | 442 | 244 | 1995 | 2013 | 1966 |
| LIGHT/I-R POST | 27 | 940 | 78 | 541 | 340 | 1955 | 1972 | 1925 |
| ELRIED HAGNETS | 19 | 677 | 78 | 1372 | 100 | 2275 | c2as | 2245 |
| LRTRASONIC POST | 25 | 1598 | 78 | 1624 | 293 | 3547 | 3664 | 3617 |
|  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
| NAR-BPND FM PHRSE | 42 | 208 | 152 | 38 | 127 | 565 | 610 | 615 |
| WID-ERAND FM PHASE | 532 | 81 | 154 | 37 | 209 | 1012 | 1860 | 1062 |
| PLESE T-0-ARRIUAL | 472 | 616 | 343 | 148 | 262 | 178 | 1825 | 1330 |
| NOISE CORRELATION | 144 | ¢9 | 343 | 33 | 182 | 759 | 775 | 788 |
| DIRECTION FINDER | 7 | 89 | 91 | 18 | 154 | 378 | 348 | 348 |
| CLRSS IU |  |  |  |  |  |  |  |  |
| TRRFFIC LCOPS | 15 | 15476 | 78 | 2572 | 323 | 18403 | 18462 | 18462 |
| HAYSIDE RADIO | 14 | 13709 | 78 | 2142 | 572 | 16514 | 16514 | 16514 |
| PHOTOLI-R DEJECT | 22 | 9114 | 78 | 1886 | 338 | 10636 | 10636 | 19636 |
| ULTRASOMIC DETECT | 23 | 9208 | 78 | 1885 | 338 | 10731 | 19731 | 10731 |

Table 2－40．Los Angeles，West Bureau AVM Polling Cycle Times

LICLE THIE IN SECOMDS TO POLL HAR AIS MIH UIITS DEFLOKED

| $\begin{aligned} & \text { CLASS I } \\ & \text { TECEHICNE } \\ & \text { TEYORPJ } \end{aligned}$ | TOTAL FLEET ta 0 | $\begin{gathered} \operatorname{sinc} \\ 12 \\ 45 \\ 49 \end{gathered}$ | SIMFLE 1318 18 439 | $\begin{array}{r} \text { Fendg } \\ 25 \quad 51 \\ 859 \end{array}$ | $\begin{array}{r} \text { SYHE } \\ 124+2 \\ 4+47 \end{array}$ |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| STMUS IAPP | 20 50 | 1318 | 1373 | 20.05 | 1451 | 1570 | 2870 |
| E－ACCELEPTIETERS | 201 | ${ }_{42}^{4} \begin{gathered}37 \\ 79\end{gathered}$ | 13 ${ }^{58}$ | 3 25 | 138 | ¢ ${ }_{15} 25$ | a 57 |
|  |  | 420 |  | 358 | 4 ¢3 | 56 | － 3 |
| LRCER UELCCIHTR | 2625 | 12 c | 1357 | 2590 | 1420 | 154 | 20 24 |
| ULTFRSSMIIC UELO | 人0 | 12 管 | 13.42 | ${ }^{8} 86$ | 13.7 | 515 | 378 |
|  |  | So | $4{ }^{4}$ | \％ 58 | 463 | ${ }^{5} 50$ | ${ }_{6}$ |
| COHPRSS／ODEMETEP | $20 \% 1$ | 129 | 1342 | 2574 | $13-9$ | 1513 | $\checkmark 5$ |
|  |  | 736 | $4{ }^{7}$ | 858 |  | 5 Br | 93 |
| CORIPRES／LASEP VEL | 2091 | 1279 | $13+2$ | 257 | 1538 | 1513 | こ8 ロ |
|  |  | $\bigcirc$ | 747 | 358 | $\checkmark 6$ | 51. | 3 is |
| CImSSU－CORIIC IEL |  | 12 | 1342 | 257 | $13 \%$ | 1513 | 20 |
| Orecr | 2159 | 1381 | 14.43 | 2075 | 1591 | 17 10 | 2011 |
|  |  | $\checkmark 60$ | $\rightarrow$ 81 | 39 | 53 | 57 | 16 ch |
| Leffit | 2 2 | 1420 | 14 | 2714 | 10.6 | 15 | 30.5 |
|  |  | 473 | ${ }_{14}{ }^{4} 94$ | \％ 295 | 15 | 15 80 | 19 |
| deccem | 3190 | $1 \times 34$ $\rightarrow 08$ | 14 ${ }_{4}^{46}$ | ${ }^{5654}$ | 15 | ${ }^{15}$ | 305 |
| RTM－STATIOTS | 1976 | 126 | 1320 | C5 58 | 13 y | 1432 | 2777 |
|  |  | $7{ }^{21}$ | $4+2$ | ${ }^{3} 53$ | 45 | $7{ }^{7} 9$ |  |
| J．f |  |  | 481 | －\％ | 530 | 175 | 1012 |
| DIff Lorfu | 22 20 | 1．000 | 14.32 | 2714 | $105^{\circ}$ | 1794 | 3489 |
|  |  | T | $4+4$ | 345 | 550 | 5 | 10\％ |
| SIFF Al－STH | 21.7 | 1373 | 14 | E0 68 | 1570 | 1500 | $2^{4} 4$ |
| RELAY OIEGA | 189800 | 11315 | 11い ${ }^{78}$ | $1144^{3} 8$ | 235179 | 23s3 ${ }^{5}$ | 23054 |
| Relar oncca | 28＊ | ～93 \％ | 30111 | 303 | －23 m | ${ }_{73}$ | 128 6 |
| RELegy Lorfti | 300 | 5970 | 513 | 03 bs | 37 | 94195 | 1430 |
| Lass It |  | 164 | 1711 | 2182 | $\infty$ | 3u | ごって |
| EUPIED PES LOOPS | 2913 | 12 g | 13.4 | 2582 | $1.0{ }_{4}$ | 15.9 | 28 E |
|  |  | 4 24 | －51 | ${ }^{8} \mathrm{D} 1$ | $7{ }^{6-5}$ | 510 | ${ }^{8} 1$ |
| PEFLECTING Sictis | $\therefore 13$ | 1287 | 13.49 | 25 | $14{ }^{1}$ | 15 | $\mathrm{Cl}_{2}$ |
| REFLECTINE PGAD | 2013 | 1287 | $1{ }_{13}^{4}$ | － 381 | 14154 | 1529 | $20^{5}$ |
|  |  | ＋ 29 | 75 | $8{ }^{81}$ | ${ }^{7}$ tS | 510 |  |
| －5aty most | 2031 | 12 | 13 ＋ | ¢5 | 138 | 15 13 | \％以 |
| H゙ IMF FUST | 1270 | 120 | $10^{3} 85$ | 25 | $13 \frac{63}{5}$ | 14 \％\％ | 2－36 |
|  |  | $\bigcirc 31$ | 4 | 053 | $\angle 52$ | $4{ }^{4}$ | $\square{ }^{4}$ |
| LF FOST | 2981 | $1 c^{\text {ca }}$ | 13 4a | 57 | 130 | 1513 | ctu |
| LICHT／I－R POST | 2031 | 1279 | $13{ }^{4}+1{ }^{4}$ | $25 \cdot 5$ | 13 | 5 <br> 15 <br> 13 | 年 |
|  |  | 420 |  | $\bigcirc 5^{3}$ | －63 | 50 | \％ 3 |
| SURIES HGGIETS | cิv 13 | 12\％ | 13 7 ${ }^{4}$ | 25 ${ }^{\text {c }}$ | 1．04 | 158 | 起 |
| ULTPASOUTIC FOST | 2u91 | ${ }_{12}{ }^{23}$ | $\geq 5$ | ${ }^{\circ} \mathrm{s}$ | －© | 510 | 3208 |
|  |  | －20 |  | 35 | ¢ 53 | 5 | 28030 |
| TRAFFIC SEITSOR | 2001 | 1279 | $13+2$ | 257 | 1388 | 1513 | ¢ 0 0 |
|  |  | 486 | $\rightarrow{ }^{+}$ | 353 | $\cdots$ | 50. | $y 36$ |

Table 2－41．Los Angeles，West Bureau AVM Accuracres and Cost Benefits with One Radio Channel

|  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  |  |
| CLRSS I |  | UEHICLES | S SYSTEM |  | UEHICLES |  | ESTIIIRTED 5－YERs |
|  | ULTIHATE |  |  |  |  |  |  |
|  | Pacy | SAUED | MPX | MIN | MRX | Hin | sajilic |
| YEYELARD | 33 | 7 | 459 | 157 | 20 | 08 | 935 |
| STALUS MAP | 30 | 7 | 495 | 163 | 1.9 | 40 | 909 |
| 2－ficceleroriziers | 34 | 7 | 467 | 160 | 1.9 | 0 | 830 |
| LFSER UELOCIMTR | 13 | 3 | 459 | 157 | 2 － | 0 | 86 |
| ULTRRSOHIC VELO | 40 | 7 | 469 | 161 | 19 | 09 | －85 |
| COMPRES－ODOMETER | 20 | 8 | 469 | 157 | $2 \square$ | 6.6 | 960 |
| COTPRSSALASER UEL | 15 | 8 | $45 \overline{0}$ | 156 | 20 | 0 | 315 |
| CHPSS／U－SONIC UEL | 17 | 8 | 458 | 156 | 20 | 9 | 915 |
| 014cis | 1598 | 8 | 4227 | 4037 | 00 | 00 | 9 |
| LORAN | 160 | 4 | 53.4 | 40.4 | 3 | 40 | 20 |
| DECCA | 200 | 3 | 518 | 487 | 95 | 139 | －195 |
| fithestations | 290 | 3 | 508 | 485 | 0.5 | 08 | －130 |
| DIFF OMECA | 169 | 4 | 521 | 464 | $0 \cdot 3$ | B 5 | 34 |
| DIFF．LGRPM | 400 | 1 | 1177 | 1119 | 00 | 00 | $t$ |
| DIFF FMM－STA | 250 | 2 | 623 | 536 | 96 | （1） 1 | 0 |
| pelay orega | 500 | 0 | 40187 | 13565 | 00 | 00 | 0 |
| RELAM LOPAM | 300 | $\square$ | 2164 | $229+$ | 00 | 00 | $G$ |
| CLASS 11 |  |  |  |  |  |  |  |
| JUPIES RES－LOOPS | 10 | 8 | －54 | 155 | 20 | 64 | 985 |
| PEFLECTING SIGNS | 19 | 8 | 454 | 155 | $2 \cdot 0$ | 00 | 46 |
| REFLECTING RORD | 3 | 8 | 438 | 145 | 20 | 08 | 4655 |
| －EAHD POST | 12 | 3 | 454 | 155 | 20 | 40 | 235 |
| HEF，URIF POST | 15 | 8 | 452 | 154 | 20 | 95 | －10－ |
| LF POST | 103 | 6 | 481 | 267 | 15 | 0.0 | －95 |
| LICHT／I－P POST | 39 | $?$ | 465 | 159 | 29 | 00 | 209 |
| BUPIED MAEMETS | 4 | 8 | 442 | 151 | 20 | 90 | 186 |
| ULTRASONIC POST | 39 | 8 | 460 | 157 | 20 | 9 ¢ | 35 |
| TRAFFIC SEEASOR | 18 | 8 | 451 | 154 | 2.6 | 08 | 90 |
| CLASS III |  |  |  |  |  |  |  |
| NFP－EAND FIT FARTSE | 1889 | 9 | 2717 | 2576 | 00 | 00 | 9 |
| LID－EFAD FH PHRSE | 1200 | 0 | 3194 | 3051 | 00 | 0.0 | 0 |
| PULSE T－0－ARRIUFL | 188 | 6 | 193 | 183 | 18 | 35 | 16.15 |
| NOISE CORPRELATION | 100 | 6 | 216 | 205 | 1.7 | 3.0 | 1340 |
| CLHSS IU |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
| Herrside radio | 180 | 6 | 201 | 212 | 17 | 34 | －310 |
| PHOTOI－R DETECT | 30 | 7 | 59 | 62 | 24 | 6.7 | 3335 |
| ULTRASONIC DETECT | 20 | 8 | 42 | $\rightarrow 4$ | 25 | 71 | 3635 |

LAMEST EUREFE

| CLASS I TECTHICUE | SYSTEM A | ICCURACIES |  | $\begin{aligned} & \text { UEHICLESS } \\ & \text { SYSTEE } \end{aligned}$ | ESTIMATED |  | \＄1868 | SPMIHES ESTIMATED |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | THEO |  |  | VEHI |  |  |  |
|  | HATE | VERICLES |  | cy |  |  |  | 5－YEPR |
|  | Rficy | SRYED | MRX | HIN | Mex |  | MIN | SRUIMG |
| KEYBCPRD | 33 | $?$ | 236 | 94 | $2-2$ |  | 2.5 | 1368 |
| STYLUS MPP | 39 | 7 | 244 | 88 | $2 \cdot 3$ |  | 2.3 | 1290 |
| 2－ficem srouneters | 34 | 7 | 240 | 98 | $2 \cdot 2$ |  | 2.4 | 1285 |
| LRSER VELCCIMTR | 13 | 8 | 236 | 77 | 2－3 |  | 2.5 | 1235 |
| LLTRASOHIC VELO | 46 | 7 | 241 | 108 | 2．2 |  | 2．4 | － 1160 |
| COHPASS／ODOHEIER | 20 | 8 | 236 | 77 | 23 |  | －5 | 1335 |
| COHPASSALASER MEL | 15 | 8 | 234 | 77 | 2.3 |  | 6 | 1365 |
| Cresshu－SOHIC VEL | 17 | 3 | 235 | 77 | $2 \cdot 3$ |  | －6 | 1355 |
| OHECA | 1063 | 0 | 4106 | 3922 | 0.0 |  | 0.0 | 0 |
| LORAN | 160 | 4 | 411 | 393 | 0.9 |  | 0.8 | 105 |
| IECCA | 209 | 3 | 495 | 473 | 05 |  | $0 \cdot 6$ | －195 |
| fti－STATIOtS | 208 | 3 | 493 | 471 | 05 |  | 0 | －180 |
| IIFF．OHECA | 160 | 4 | 411 | 392 | 99 |  | 0 | 105 |
| DIFF．LORAN | 400 | 1 | 1148 | 1884 | 98 |  | a | $\theta$ |
| DIFF．RM－STH | 250 | 2 | 596 | 569 | 01 |  | a | －480 |
| SHETHY OHECA | 509 | 0 | 20449 | 6450 | 00 |  | 0 | $\theta$ |
| PEIFIT LOREA | 860 | 8 | 23.48 | 2218 | 00 |  | 0 | $\theta$ |
| CLPES II |  |  |  |  |  |  |  |  |
| BURIED RES LOOPS | 18 | 8 | 233 | 70 | 2－3 |  | 6 | 1435 |
| REFLECTIHG SIGNS | 10 | 8 | 233 | 76 | 2.3 |  | 6 | 490 |
| REFLECTIHG ROAD | 3 | 8 | 224 | 7 | 2－3 |  | －8 | －4055 |
| X－EATD POST | 12 | 8 | 233 | 76 | $2 \cdot 3$ |  | 6 | 735 |
| 1F，UF POST | 15 | 8 | 231 | 76 | 23 |  | 6 | 1260 |
| IF POST | 100 | 6 | 273 | 259 | 1.5 |  | 7 | 55 |
| LIEHT／I－R POST | 38 | 7 | 239 | 83 | 2.3 |  | 5 | 175 |
| BURIED MGGHETS | 4 | 8 | 226 | 75 | $2 \cdot 3$ |  | ． 3 | 1689 |
| ULTRASONIC POST | 28 | 8 | 236 | 77 | 2.3 |  | ． 5 | 410 |
| TRFFIT SENSCR | 10 | 8 | 231 | 76 | 2.3 |  | ． 6 | 1440 |
| CLASS 111 |  |  |  |  |  |  |  |  |
| WWR－ERHLD PI PHASE | 1068 | 8 | 2627 | 2491 | 6－8 |  | － 0 | 0 |
| HID－EPED FM PHASE | 1200 | a | 3103 | 2958 | 0.0 |  | － 0 | 0 |
| PUESE T－O－ARRIUAL | 108 | 6 | 193 | 183 | 1.8 |  | 3.5 | 1615 |
| HOISE CORRELATION | 100 | 6 | 216 | 205 | 1.7 |  | 3.0 | $13 \sim 0$ |
| MIRECTION FIMIER | 760 | 0 | 1933 | 1832 | 0.0 |  | ． 6 | $\square^{3}$ |
| CLFESSIV IVA | 19 | 3 | 32 | 04 |  |  |  |  |
| HAYSIDE RADIO | 100 | 6 | 281 | 212 | 2.6 1.7 |  | ． 6 | 4060 310 |
| PHOTOVI－R DETECT | 30 | 7 | 59 | 62 | 24 |  | ． 7 | － 3335 |
| ULTRRSONIC DEIECT | 20 | 8 | 42 | 44 | 2．5 |  | －1 | 3635 |

Table 2－43．Los Angeles，West Bureau AVM Accuracies and Cost Benefits wath Three Radio Channels

| CLASS I | STSTEM P | CCURACYES 00.0 VEHICLES PATD |  |  | ESTIMATED S1900 |  | SAUINGS ESTIMATED |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | ULTIHATE PCCIPSCY | THICU SS RYSTEM |  |  |  |  |  |
|  |  | SAUED | MPX | MIM | MAX | Min | Sfuimg |
| KEYBOPRD | 33 | 7 | 157 | 92 | 2 | 44 | 2785 |
| STYLUS HAP | 39 | 7 | 163 | 81 | 2.3 | 43 | 2708 |
| 2－ficcemeroreters | 34 | 7 | 168 | 96 | 2.2 | 43 | 2630 |
| LRSER UELOCIHTR | 13 | 8 | 157 | 54 | 2.4 | 4.4 | 26ヵ0 |
| ULTRRASONIC UELO | 49 | 7 | 161 | 185 | 22 | 4.3 | 2585 |
| COTMPRSS－ODOTETER | 28 | 8 | 157 | 51 | 24 | 4.4 | 2760 |
| COMPRSS／LASER UEL | 15 | 8 | 156 | 54 | 24 | 4.4 | 2715 |
| CHPSSAT－SDNIC UEL | 17 | 8 | 156 | 54 | 24 | 44 | 2715 |
| OrEGA | 1609 | 9 | 4037 | 3856 | 0 | 0 | 0 |
| LCRXA | 160 | 4 | 404 | 336 | 09 | 00 | 105 |
| DECCA | 209 | 3 | 487 | 465 | 06 | 60 | －120 |
| RIV－STATIDMS | 280 | 3 | 485 | 463 | 06 | 54 | －105 |
| DIFF．OTREA | 150 | 4 | 484 | 386 | 09 | 0 | 105 |
| DIFF．LOAFA | 400 | 1 | 1119 | 1063 | 0 | 96 | 0 |
| DIFF．AK－STA | 258 | 2 | 586 | 560 | 0.1 | 0 | 480 |
| RELPY OTEGA | 509 | 0 | 13565 | 4437 | 0.0 | 0 － | 9 |
| RELAIM LORFM | 863 | 0 | 2294 | 2175 | 00 | 99 | 0 |
| CLISS II |  |  |  |  |  |  |  |
| ZURIED FES LOOPS | 10 | 8 | 155 | 53 | 24 | 45 | 2980 |
| REFLECTING SIGHS | 16 | 8 | 155 | 53 | 24 | 4.5 | 1915 |
| REFLECTIFG RORD | 3 | 3 | 149 | 52 | 2.4 | 46 | －2795 |
| 人－Benm POST | 12 | 8 | 155 | 53 | 24 | 45 | 2160 |
| HF，UFF POST | 15 | 8 | 154 | 53 | 24 | 45 | 2685 |
| LF POST | 109 | 6 | 267 | 254 | 15 | 18 | 120 |
| LIGHT／I－R POST | 38 | 7 | 159 | 88 | 23 | 44 | 1060 |
| BURRIED MPGHETS | ＋ | 8 | 151 | 52 | 2.4 | 46 | 2950 |
| LLTRRSONIC POST | 20 | 8 | 157 | 51 | 2.4 | 44 | 1035 |
| TAPFFIC SEMSOR | 16 | 3 | 154 | 53 | 24 | 45 | 2065 |
| CLASS 111 |  |  |  |  |  |  |  |
| NHR－ZAAD FM PHASE | 1860 | 0 | 2576 | 2442 | 90 | 00 | 0 |
| HID－DFAHD Fil PYR2SE | 1200 | 6 | 3851 | 2900 | 09 | 0 | 0 |
| PULSE T－O－PRRRIUFL | 100 | 6 | 193 | 183 | 18 | 35 | 1615 |
| NOISE CORRRELATIOM | 108 | 6 | 216 | 205 | 1.7 | 3.0 | 1ごひ |
| DIRECTION FIMDER | 780 | 0 | 1895 | 1797 | 0.8 | － 0 | － |
| CLASS IU |  |  |  |  |  |  |  |
| TRAFFIC LOOPS | 18 | 8 | 22 | 24 | 2．6 | 7.6 | cube |
| WPYSIDE RADID | 180 | 6 | 281 | 212 | 17 | 34 | O10 |
| PHOTOL－R DETECT | 30 | 7 | 59 | 62 | 24 | 67 | 3335 |
| ULTRASONIC DETECT | 28 | 3 | 42 | 44 | 25 | 71 | 3635 |

Table 2－44．Los Angeles，Valley Bureau AVM Physical Parameters

［AST HEST DISTAMCE IE ES HILES．
HORTH EOUTH IIETRHEE IS 13.5 HILES．

TrIE HUTIEEF OF INTEFSECTIOHS IS 15000

fhefe fre log chfs ill the fleet．
Fiti Thefe are a motafcicles．
THE HMEEF 日F vehicles on Efich shift $1 \approx$ ．
first inirt he．Te

FIFST EHIFT HIH．$\in 1$
SECTIS EHIFT MA… $19 E$
seconio shift mili．ac

THIFD EHIFT HRK．IEA

THIRI EHIFT HIN，EE

THE IIJISEF OF IISFATCHEFミ İ こ




Table 2－45．Los Angeles，Valley Bureau AVM Systems Cost Analyses

| LH－MH2LES JUCERI） Cl｜lll |  |  |  |  |  | TUTHLS |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Tituld | 13S UF |  |  |  |  |  |
| ricintigus | Lhirs | Gites | 3FEE | In＇st | O－11 | 102 | 5 ITC | FRiturn |
|  | L－ | 4 | لJ | 17 | 143 | 25 | 45 | 2.5 |
| STiLus liap | $\rightarrow \hat{c}^{\text {c }}$ | U | J | 17 | 16 | －1．4 | 68. | 60 |
| ¢－HCCELEPOIL TCFS | 313 | 0 | 115 | 29 | 11. | 597 | 63. | 625 |
| Lh Ef HELOLidita | 357 | 0 | 114 | 36 | 129 | r5f | $r 37$ | 053 |
| ULTRIMSURIC IEELU | $2+1$ | ${ }_{1}$ | 119 | 29 | 129 | 547 | 534 | 575 |
| Culifics\％obilictep | CTt | $\square$ | 119 | 1－ | 1 y | 3.8 | 543 | $5-4$ |
|  | 351 | 0 | 119 | 3 | 110 | 05 | 791 | 032 |
| CHPうこM－SOMIL MEL | 209 | $u$ | 111 | 69 | 112 | $5{ }^{5}$ | －33 | 0.13 |
| い⿺𠃊⿻丷木斤丶 | 511 | 4 | 100 | 26 | 115 | F30 | 330 | 819 |
| LDERA | 530 | 1 | 163 | 26 | 115 | 73 | 8，9 | $\checkmark \square 1$ |
| Sedh | ぎい | $\square$ | 103 | 22 | 115 | 4 － | 53. | 524 |
|  | To | 0 | 100 | 20 | 110 | 337 | 373 | ¢r |
| JIFF UtEGA | 511 | 1 | 1 10 | 20 | 115 | $\cdots$ | －16 | 810 |
| 3IFF LUPMil | 530 | $v$ | 109 | 26 | 115 | 74 | －35 | 241 |
| gita minsta | c8 | 0 | 193 | 29 | 112 | 2－9 | 335 | 74 |
| PCLHY uneta | 140 | 1 | 109 | 36 | 115 | 37 | 3－4 |  |
| PELAY LUPRH | $16^{9}$ | 0 | 100 | Z | 119 | 333 | 353 | 439 |
| CLh5E II |  |  |  |  |  |  |  |  |
| SIPIET KEA LuOPS | 27 | 1ヵアコ」 | 80 | 18379 | 145 | 24．17 | 2ロ436 | 2＋308 |
| Ftrlecting siblls | 1 | 3340 | 80 | 1339 | 40.4 | 57.44 | 5762 | 513 |
| FEFLECTIHG PDAS | E． | 266 | 80 | 21E2 | 1903 | －579 | $\rightarrow 590$ | 45.48 |
| S－EMHI FOST | 0 | $3+59$ | 80 | 093 | 327 | 4012 | 7630 | 45 yc |
| HF＇，UHF POST | उ | 375 | 80 | 167 | 154 | 057 | S＂7 | ¢9\％ |
| LF PUST | －7 | 1875 | 80 | 094 | 328 | 3435 | 3053 | 3095 |
| LIGHT－I－F POST | 33 | 1500 | 60 | 359 | 480 | 2907 | 29\％5 | 2937 |
| BUF IED LIASUETS | 19 | 1080 | 8 | 2179 | 100 | 3488 | 35 fto | $3 \rightarrow 58$ |
| ULTPRSOHLC POST | 26 | 2550 | 811 | 2577 | 495 | 5067 | $5 \mathrm{bo5}$ | $5 ¢ 37$ |
| TRAFFIC SELLSGR | 28 | 2850 | 60 | 1218 | 182 | －308 | ¢020 | ＋2ア7 |
| CLASS II I |  |  |  |  |  |  |  |  |
| NAP－BATIC FIT PHASE | $\rightarrow 3$ | 212 | 157 | 39 | 123 | 577 | 24 | 029 |
| HIS－Eriju Fil phfise | 550 | 115 | 104 | 43 | 210 | 1031 | 1150 | 1133 |
| PULSE T－U－FRRIVHL | $4{ }^{+}$ | 630 | $3 \times 9$ | 151 | 203 | 1819 | 1 160 | 1871 |
| HOISE CORRELATION | 149 | 29 | 349 | 3 | 192 | 771 | 738 | 793 |
| IIPECTIOH FINDER | 7 | 50 | 98 | 18 | 15. | 378 | 355 | 355 |
| CLRSS IV ${ }_{\text {TRAFFIC }}$ | 10 | 20633 | E0 | 4091 | 462 | 25281 | 25231 | 25281 |
| WATSİE RADIO | 15 | 13176 | U | 3－48 | 352 | 22529 | 225ea | 2cse9 |
| FHOTO\I－R DETECT | 22 | 11928 | ¢0 | $1{ }^{10} 19$ | $\rightarrow 78$ | $1 \mathrm{mez5}$ | 14225 | 1＋225 |
| ULTFASOHIC DETECT | 24 | 12078 | $\cdots$ | 1718 | 478 | $1+36$ | 1－1376 | 14370 |

Table 2－46．Los Angeles，Valley Bureau AVM Polling Cycle Times


| CLASS I TECHHIMUE | TOTAL FLEET | STHC | 3 ITPLE | EAng | SYHC | REDUHJPITT Jot | Rent |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| YEYEORRS | 28 29 | 1299 | 1303 | 2638 | 1383 | 1517 | 2855 |
|  |  | $\bigcirc 55$ | $\bigcirc 87$ | 1330 | 7.08 | 705 | $1-4$ |
| STYLUS ItPP | 2117 | 1355 | 14.20 | 369 | 1596 | 1089 | 2909 |
|  |  | 13 | $7{ }^{16}$ | 1358 | 175 | \％マ |  |
| CELEPOMETEPS |  | 1323 | 13.38 | 20－82 | 14.36 | $15{ }_{8}^{65}$ | 2900 |
| Lasep nelocintr | 2992 | 13 | 14.84 | 2678 | 1463 | 1597 | 2930 |
|  |  | 675 | 768 | 1350 | $7{ }^{7}$ | 205 | 1480 |
| ULTPHSOHIC JELEO | 2000 | 1523 | 1358 | 206 | 1.30 | 15.5 | 2964 |
|  |  | 68 | 7 ve | 13.42 | 7 － | 789 | 146\％ |
| COMPRSS／OJOHETER | 200 | 1323 | 1388 760 | 2603 | 1430 | 1565 |  |
| COMPASS／LASER VEL | 20 －5 | 1523 | 13 w | 26 c | 1430 | 1565 | 2a ut |
|  |  | ¢ 3 | 740 | $13+2$ | 72 | 8 | 1． 69 |
| ErPSSU－SCHEC IEL | 20 0\％ | 1383 | $13 \%$ | $\underline{6602}$ | 14.30 | 15.5 | $\mathrm{c}^{-9} 0$ |
| Oifeg | 2230 | 087 $1+88$ | 790 1498 | 13.42 | 784 10 40 | ${ }_{17} 7^{89}$ | 14  <br> 31 15 <br> 15  |
|  |  |  | 752 | 1295 | 3 30 | 8 | 1570 |
| LOFrat | 2E 93 | 146 | 1533 | 2367 | 1720 | 1055 | 31.04 |
|  |  | －40 | 773 | 1715 | 370 | 935 | It 10 |
| jecca | 2e $\% 3$ | 1459 | 1517 | 2741 | $10{ }_{4}$ | 1823 | 31 b2 |
| HH1－STATISH | 2041 | 1387 | ${ }_{13}{ }^{7} 85$ | ${ }_{3}^{16} 97$ | ${ }_{54}{ }^{3} \mathrm{SH}$ | 4 15 30 | 158 |
|  |  | － 59 | 6 y1 | 153. | －98 | 773 | 14.7 |
| JIFF OIIECH | 2e 20 | 1426 | 14.92 | 47 br | 15.6 | 1785 | 3117 |
|  |  | 720 | 75 | 13 ys | 3 H | ${ }_{6} 9$ | 158 |
| JIFF Lornd | 22 93 | $1 \pm 68$ | 1533 | 2367 | 17 E | 1455 | 314 |
| SIFF NU1－STA | ¢兀 18 | 1429 | 1.4 | 17 15 | ${ }_{18} 80$ | ${ }_{17}^{935}$ | 10 34 36 |
|  |  | 710 | 7 \％ | $13{ }^{1}$ | \％ | ${ }^{17} 87$ | 15 |
| RELf M Miekf | 190390 | 122219 | 122275 | 123549 | 2432－16 | 243539 | 2446 73 |
|  |  | b10 19 | blb 7 | 622 85 | 1220110 | 1225 75 | 100356 |
| RELFY LURAIt | 8190 | 5243 | 5308 | 6532 | 92 TP | 9 OH | 10745 |
| Clims II |  | 2043 | 2670 | 3318 | $\cdots \mathrm{T}$ ？ | －＂ 42 | 5417 |
| JupIED PES LOOPS | $207^{\circ}$ | 1331 | 13.96 | 26 \％${ }^{6}$ | 1452 | 1581 | 20.4 |
|  |  | \％ 71 |  | 13 |  | 97 |  |
| PEFLECTItic SICHS | 2070 | 1331 | 13 B | 25 T | 145 | 1581 | Cacol |
|  |  |  | ${ }^{7} \mathrm{Ba}$ | 13.75 | 7 \％ | ${ }_{5} 9$ | 1－ |
| PEFLECTILS ROAD | 207 | 1331 | $13{ }^{9}$ | \％ 70 | 1453 | 1531 | ¢9 こu |
| －Eftig Posy | 2006 | 571 1023 | ${ }_{13}{ }^{7}$ U゙ | 15006 | 732 1436 | $\begin{array}{r}7 \\ 15 \\ \hline 05\end{array}$ | 149\％ |
| －3an Past | －0 | 10 0 6 | 730 | 13 | $\underset{1}{1+3}$ | $\bigcirc$ | $1 \times 6$ |
| HF，M－F POST | 28 41 | 1367 | 1371 | 2645 | 10.94 | 1533 | 2972 |
| LF POST | 20 06 | $1{ }_{13}{ }^{59}$ | m 13 88 | 15 20 20 | 1745 | 7 73 | 14.8 |
|  |  | 6 br | 76 | $13 \rightarrow 2$ | 17 \％ | 156 |  |
| LIEHT／I－R POST | 20 －0 | 13 | 1388 | 20.0 | 1730 | 158 | 2\％6． |
|  |  |  | 7 ย0 | 1242 | $7 \mathrm{\square}$ | －89 | 1400 |
| BURIEJ TAGCNETS | 2079 | 1301 | 13.46 | 2679 | 1452 | 15.81 | 24 29 |
| ULTEASONIC PAST | 20 60 | ${ }_{13}{ }^{8} 71$ | ${ }_{13}{ }_{8}{ }_{8}$ | 13.96 | － 20 | 797 1585 | 1．73 |
|  |  | $\bigcirc 07$ | 740 | 1342 | ［ 4 | 15 |  |
| TRAFFIC SEHSOP | 20 －0 | 1323 | 1388 | 20 | 1－30 | 15 \％ | 29 ¢ $^{\text {a }}$ |
|  |  | 067 | 760 | 1342 | こ。 | － 89 | דט ד1 |

Table 2-48. Los Angeles, Valley Bureau AVM Accuracies and Cost Benefits with Two Radio Channels

|  | تISTEN |  |  | Les ${ }_{\text {ata }}$ | estimated IEHICLE |  | skuings estimated |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | venicles |  | RRC\% |  | Hin |  |
| KEISOPRD |  |  |  |  |  |  |  |
| Stube itep | 30 | 3 | 553 | 120 | 3.4 | 3 | ${ }_{20}$ |
| 2-HCEELEPGIETERS | S ${ }^{34}$ | 3 | 2.38 | 12. | ${ }^{3}$ | 35 | 30se |
|  | 13 |  | 244 | 123 | 3 | \% |  |
| Gipmoshic uelo | ${ }^{9}$ | $3$ | $2 \cdot 9$ | 125 | 3 | 3.5 | 1909 |
| COIPASSRLISER | (15 | $\begin{aligned} & 3 \\ & 3 \end{aligned}$ | 3, | ! |  | 3080 |  |
| CIIPSS | UEL ${ }_{\text {IT }}$ |  | 243 | 121 |  | $\bigcirc$ | 2116 |
| ORIECA | 1690 | u | -112 | 3090 | ${ }_{0} 0^{\circ}$ | $0_{0}$ |  |
| LGRem | 114 | - | 412 | , 3 |  |  | T5 |
| CF | Eua | 5 | -96 | 482 | ${ }^{8}$ | 80 | S |
| Silstaniols | 200 | 5 | $\rightarrow 7$ | Tes |  |  |  |
|  | ${ }_{708}^{169}$ | 1 |  | H0u | ${ }_{14}^{4}$ | ${ }^{0}$ | 5 |
| DiFF. Etit-STA | ${ }_{253}$ |  |  | scu |  |  |  |
| RELLY UHEECA | 600 | 1 | 1141 | 10510 |  | 00 |  |
|  | 389 | - | 34 | 2267 | $0 \cdot$ | -6 | - |
| SUPIES PES LOOPS | Ps 16 | 3 | 241 | 129 | 3. | 37 | \%00 |
| PEFLECTIEGG ROAD | - |  | 232 | 116 | 3. | \% | 505 |
| $\hat{A}$ | 12 | \% | ${ }_{239}$ | 1189 | ${ }^{3} 4$ | ${ }^{3} 7$ | ${ }^{1119}$ |
| ${ }_{\text {LFP Pust }}$ | 1 |  | 239 | 12 |  |  |  |
| LIEHTTI-R POST | $\bigcirc$ | 3 | ล24T | 124 |  |  |  |
| ExPled Ifighets | - | 8 | 弱 | 117 | ${ }_{3}$ | 38 | 2359 |
| Iltrassumic poit | ${ }^{2}$ | 3 | $\underline{-4}$ |  |  |  |  |
| arfic serisor | 19 | \% | 239 | 119 | - | 37 | ¢265 |
| MAP-EARTD FIM PHASE | SE 1000 | $\bigcirc$ | ${ }^{2031}$ | $25+5$ | 09 | vo | $\bigcirc$ |
|  |  |  |  |  |  |  |  |
| HOISE COPPELATIOM | ${ }_{\text {OH }}{ }^{\text {OL }}$ |  | ${ }_{217}^{174}$ | ${ }_{268}^{138}$ | -7 | $4{ }^{\circ}$ | ${ }_{2}^{2+355}$ |
| PIPECTIOM FINDER | 8 793 | 8 | 1936 | 1872 | - | 06 |  |
| TRPFFIC Lo |  |  |  |  |  |  |  |
| MPYSIDE PARID | 199 | 5 | 268 | 29 | 28 | $\stackrel{3}{4}$ | 3805 |
| PULTRASOHIC DETECT | CT | ${ }_{8}^{8}$ | ${ }_{4}^{59}$ | ${ }_{4}$ | ${ }^{3} 9$ | 78 | 3305 |
|  |  |  |  |  |  |  | 3310 |

Table 2-49. Los Angeles, Valley Bureau
AVM Accuracies and Cost Benefits with Three Radio Channels


## PART THREE:

# ANALYTICAL TECHNIQUES FOR ESTIMATING AVM SYSTEM ACCURACY 

J.E. Fielding<br>M. Perlman

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Joseph E. Fielding

## I. VEHICLE LOCATION ACCURACY FOR CLASS I AND III SYSTEMS

In this Section, an algorithm $1 s$ described which can be used to determine the system accuracy of Class I and III automatic vehicle monitoring (AVM) systems as a function of the appropriate system parameters. Some of the resultant cumulative probabılity density functions (cdfy) are also presented, which can be interpreted as the fraction of the fleet for which the error is less than or equal to $y$. The flow chart shown in Fig. 3-1 is a brief outline of the vehicle location accuracy program, while Fig. 3-2 expands on the methodology of the computation of the cumulative density function.

## A. Parameters for AVM System Accuracy Analysis

The inherent exror, ${ }^{\circ} \mathrm{o}$, is defined to be the distance between the vehicle's actual location and the location determined by the AVM system at the


Fig. 3-1. Main AVM Accuracy Analysis Program


Fig. 3-2. Computation of Cumulative Distribution Function
instant of polling. Inherent error is assumed to be consistent with a Rayleıgh distribution, 1.e.,

$$
\Phi\left(\epsilon_{0}\right)=\frac{\epsilon_{o}}{\sigma^{2}} e^{-1 / 2\left(\frac{\epsilon_{0}}{\sigma}\right)^{2}}
$$

As time passes, the vehicle's location changes by a distance of ( $s, t$ ) and a direction $\theta$. (See Fig. 3-3.) The random variable $\theta$ is assumed to be uniformly distributed. Its probability density function is denoted by $p(\theta)$, and is equal to $1 /(2 \pi)$ between $-\pi$ and $\pi$.

The speed of the vehicle is represented by the symbol $s$ and is assumed to be described by the following distribution

$$
f(s)=\left\{\begin{array}{l}
F O \cdot \delta \quad s=0 \\
\lambda e^{-\lambda s} \quad 0<s<M \\
0 \quad \text { otherwise }
\end{array}\right.
$$



Fig. 3-3. Error in Knowledge of Vehicle's Location

There is a discrete probability FO, associated with zero speed. Between speeds zero 0 and maximum M , the speed is distributed exponentially. The parameter $\lambda$ is set such that the fraction of vehicles stopped, FO, plus the fraction whose speed falls between 0 and maximum speed $M$ sums to 0.99 .

The last of the AVM system parameters 15 time. After the location of the vehicle is determined, there is a delay before the information becomes available. This delay is referred to as computation time, $\mathrm{T}_{\mathrm{C}}$. Thus, if the symbol T denotes the polling interval, the probability density function $g(t)$ is a unıform distribution over the time interval $T C$ through $T_{C}+T$.

## B. Derıvation of Accuracy Analysis Algorithm

Probability distribution functions have been defined for $\epsilon_{0}, \theta, s$, and $t$, and from Fig 3-3 the actual error in the knowledge of the vehicle's location, $\epsilon$, is:

$$
\epsilon=\sqrt{\epsilon_{o}^{2}+s_{t}^{2}-2 \epsilon_{o}^{2} s t \cos \theta}
$$

The distribution of errors is given by:

$$
\text { cdfy }=\operatorname{Prob}(\epsilon \leq y)=\iiint \int_{R} \Phi\left(\epsilon_{o}\right) g(t)
$$

$f(s) p(\theta) d \theta d s d t d \epsilon_{o}$,
where $R$ is the region such that $\epsilon \leq y$. Due to the complexity of $R$, it is not practical to evaluate this integral analytically or by numerical quadrature. Therefore a Monte Carlo integration of cdfy is used.

The Monte Carlo integration generates values for the four random variables, $\epsilon_{o}, s, t, \theta$ and uses these variables to calculate $\epsilon$ by the above formula. By checking whether $\epsilon \leq y_{\perp}$ for $i=1, \ldots, 20$, when the $\mathrm{yi}^{\prime}$ 's are a pre-specified array of points on the abscissa, it is possible, if enough trials are run, to determine an accurate estimate of the cumulative distribution function.

The methodology used to generate the random variables $\epsilon_{0}, s, t$ and $\theta$ involves generating four uniform variates on $[0,1] \quad r_{1}, r_{2}, r_{3}, r_{4}$. Inverting the cumulative density functions leads to the expressions needed to calculate the desired variables:

$$
\begin{aligned}
& \epsilon_{0}=\sigma \sqrt{-2 \ln r_{1}} \\
& t=T_{C}+r_{2} T \\
& s= \begin{cases}0 & 0 \leq r_{3} \leq F O \\
\frac{\ln \left(1-r_{3}\right)}{-\lambda} & F O<r_{3} \leq 1\end{cases} \\
& \theta=\pi\left(2 r_{4}-1\right)
\end{aligned}
$$

Of prime concern in the Monte Carlo integration $1 s$ the number of trials needed to ensure an acceptable estimate of the probabilities that $\epsilon \leq y_{1}$. If $p_{1}$ denotes the real value of cdfy for a particulary $y_{1}$, then the process becomes a long sequence of Bernoulli trials with $p_{1}$ equal to the probability of success (i.e., that $\epsilon \leq y_{1}$ ). Since the number of trials will be "large", the Bernoullı distribution can be well approximated by the Gaussian distribution with mean, $\mu=p$
Standard deviation,

$$
\sigma=\sqrt{n p(l-p)} / n
$$

where $n=$ number of trials, and $p_{i}$ has been re. placed by p for simplicity.

Since the distribution of the number of trials for which $\epsilon$ exceeds any particular value of $y$ is approximately gaussian, we can require the probabulity (of the event that the absolute error in the distribution function, cdfy, is less than some specified maxımum value, E) to be at least $C$, the so-called "confidence level". That is, a fraction $C$ of the distribution must be contaned withon the interval $p-k \sigma$ thru $p+k \sigma$ (Fig. 3-4). Thus, a value of $C$ determines a value for $k$. In addition,


Fig. 3-4. Probability Density vs Fraction of Trials
to ensure an acceptable absolute error, E, it is required that the interval $k \sigma$ be less than or equal to E :

## $k \sigma \leq E$.

Substituting the expression for the standard deviation $\sigma$ into this last equation gives

$$
k \sqrt{n p(1-p)} / n \leq E
$$

which may be rewritten

$$
n \geq k^{2} p(1-p) / E^{2}
$$

This value for n represents the minimum number of trials needed to ensure an absolute error of less than $E$ with confidence $C$. A larger value of $k$ implies that a larger fraction of the gaussian distribution will be contaned within the interval $\mathrm{p} \pm \mathrm{k} \sigma$, thus leading to a higher confidence $C$. However, a larger $k$ requires an increased number of trials in order to satisfy the error criteria.

The accuracy algorithm specifies the maximum allowable error $E$, and the required confidence interval C. The program proceeds to run 1000 trials, and $p_{1}$ is then estimated as
(nurnber of times $\epsilon \leq y_{1}$ )/1000 for $1=1, \ldots, 20$.
These approximate values of $p_{1}$ are used to calculate the required number of trials, $n$, needed to ensure (with confidence C) that none of the error terms will be greater than the maximum allowable error E. If $n$ is found to be less than 1000 , no more runs are required and the calculation of ( $y_{1}$, cdfy) is complete. However, if $n$ is greater than 1000, additional trials are needed.

In order to prevent an excessive number of runs, in terms of computer time, a constant NMAX is introduced which serves as the maximum allowable number of trials. Thus, if it is determined that more than 1000 runs are needed, the algorithm will process additional trials untul the error terms are sufficiently small or until the maxımum allowable number of trials is reached, whichever comes first. In the case where the number of trials reaches NMAX, the resulting errors using the improved estimates of the $p_{1}$ 's are calculated. In the actual execution of the program, the number of trials is almost always extended to NMAX with resulting errors on the order of 0.005 .

The accuracy program is interactive, the user being free to set the system parameters of variance in inherent error, polling interval, computation time, fraction of vehicles stopped, and the "maximum ${ }^{\prime \prime}$ vehicle speed. The program then computes the mean of the exponential speed distribution such that $99 \%$ of the probability is included between speeds 0 and maximum speed $M$. The program also specifies the 20 values to be used along the abscissa of the cumulative distribution function of AVM system errors. These values are determined as a
function of the variance of the inherent error as one can assume that the variance of system errors is somewhat correlated with this parameter. The intent is to cover the full range from 0.0 to 1.0 of the cumulative distribution function. As a safeguard aganst fallure of full coverages, the programallows the user to calculate the cumulative distribution function for 20 additional values of $y$ where the user specifies the initial point and the interval between points. This option for additional points can be repeated as many times as the user desires. After the cumulative distribution function is computed, the user may reset the system parameters, and the process of determining a new cumulative distribution function is repeated.

## C. Results of AVM System Accuracy Analysis

The algorithm described in the previous section was exercised by running 42 cases, each one with a unique set of the input parameters, where

| SIGMA $=$ | Standard deviation of inherent error |
| ---: | :--- |
|  | in $x$ and $y$ directions |
| T | $=$ Pollıng interval |
| TC | $=$ Computation time |
| M | $=$ Maximum speed |
| FO | $=$ Fraction stopped |

Orıgınally, all combinations of the following parameter values were to be run,

| $\begin{aligned} & \text { SIGMA } \\ & \text { (meters) } \end{aligned}$ | $\underset{\text { (seconds) }}{T}$ | $\begin{gathered} \mathrm{TC} \\ \text { (seconds) } \end{gathered}$ | $\begin{gathered} \mathrm{M} \\ \text { (meters } / \mathrm{sec} \text { ) } \end{gathered}$ | FO |
| :---: | :---: | :---: | :---: | :---: |
| 0 | 2 | 0.01 | 40 | 0 |
| 100 | 10 | 0.1 | 60 |  |
| 1000 | 60 |  |  |  |
|  | 120 |  |  |  |
|  | 300 |  |  |  |

which would have required 60 cases. However, after the first 14 runs, it became evident that the AVM system error was stable for computation times in the range 0.01 to 0.1 second.

A value for the standard deviation of the inherent error of zero serves as a boundary condition for inherent accuracy of AVM hardware systems. Estimates of system error using SIGMA equal to zero represents the accuracy to be expected if one invests in extremely accurate hardware systems in terms of pinpointing location, assuming there is no motion. At first glance, a maximum speed of 60 meters /second ( 134 miles / hr) mıght seem a little high, however, the speed of the vehicles of the fleet is assumed to be distributed exponentially. Thus, a very small fraction of the fleet is traveling near maximum speeds; one-half of the fleet is traveling at a speed of less than (maxımum speed/6) or 22.3 mules $/ \mathrm{hr}$. The fraction of cars stopped is set at 0 because the algorithm is designed to specifically test system accuracy assuming moving vehicles. Later, if individual users need results that reflect their mode of operation, they can supply a non-zero value for this parameter. The effects
of changes in the above variables on AVM system accuracy follows.

No modeling effort is necessary to determine whether system accuracy will improve or deteriorate given the direction of change of any input variable. As the variance in the inherent error, the polling interval, the computation time, and the maximum speed increase, system accuracy deteriorates. However, the designer requires a more detailed knowledge of the interaction between these system parameters and AVM system accuracy. He is faced with an accuracy constraint such as $80 \%$ of the vehicles must be located to within 150 meters. In order to satisfy this constraint, he must be aware of the combinations of system parameters that can meet his requirements. The above analysis provides this information. What it does not provide is information for the designers' next step, which is to determine the proper balancewith respect to inherent accuracy, polling interval, and computation time so as to minımize cost as well as satisfy accuracy constraints.

The best accuracy results are obtaned when SIGMA is set equal to zero. Whth SIGMA zero and polling interval equal to 2 seconds, $80 \%$ of the fleet is located to within 20 meters and this is not strongly dependent on maxımum speed or computathon time. As the polling interval is increased to to 10 seconds, $80 \%$ of the fleet is located to withun 65 meters at maximum speed of 40 meters $/ \mathrm{sec}$ ond and to within 105 meters at 60 meters/second. Thus, as polling interval increases, accuracy becomes more dependent on maxımum speed. Again, the accuracy is not dependent on computation time. Table 3-1 presents similar results for the remainder of the cases with SIGMA equal to zero. The above trends continue, that is, as the polling interval increases, the $80 \%$ distance grows,

Table 3-1. Vehicle Location Accuracy at $80 \%$ Level for SIGMA $=0$ Meters

| $T(\sec )$ | $T C(\sec )$ | $M$ (meters $/ \mathrm{sec})$ | Accuracy (meters) |
| ---: | :---: | :---: | :---: |
| 2 | .01 | 40 | 15 |
| 2 | .01 | 60 | 20 |
| 2 | .1 | 40 | 15 |
| 2 | .1 | 60 | 22 |
| 10 | .01 | 40 | 65 |
| 10 | .01 | 60 | 105 |
| 10 | .1 | 40 | 70 |
| 10 | .1 | 60 | 105 |
| 60 | .01 | 40 | 420 |
| 60 | .01 | 60 | 620 |
| 60 | .1 | 40 | 420 |
| 60 | 1 | 60 | 620 |
| 120 | .01 | 40 | 820 |
| 120 | .01 | 60 | 1350 |
| 300 | .01 | 40 | 2100 |
| 300 | .01 | 60 | 3080 |

Table 3-2. Vehicle Location Accuracy at $80 \%$ Level for SIGMA $=100$ Meters

| $T(\mathrm{sec})$ | $T C(\sec )$ | $M($ meters $/ \mathrm{sec})$ | Accuracy (meters) |
| :---: | :---: | :---: | :---: |
| 2 | .01 | 40 | 180 |
| 2 | .01 | 60 | 183 |
| 2 | .1 | 40 | 180 |
| 2 | .1 | 60 | 183 |
| 10 | .01 | 40 | 195 |
| 10 | .01 | 60 | 212 |
| 60 | .01 | 40 | 448 |
| 60 | .01 | 60 | 650 |
| 120 | .01 | 40 | 850 |
| 120 | .01 | 60 | 1250 |
| 300 | .01 | 40 | 2100 |
| 300 | .01 | 60 | 3160 |

the dependence on maximum speed increases, and accuracy is not dependent on computation time.

Table 3-2 presents similar data for the case SIGMA equals 100 meters. With a polling interval of 2 seconds, $80 \%$ of the vehicles in the fleet are located to within 180 meters. The trends evident in the SIGMA equal zero cases can also be seen in Table 3-2. One major difference is that, in this case, the change in accuracy as polling interval increases from 2 to 10 seconds is rather insignificant. Thus, if the system hardware has a standard deviation for inherent accuracy in the $x$ and y direction of 100 meters, then little would be gained by specifying a polling interval shorter than 10 seconds . In comparing the results of Table 3-1 and Table 3-2, it is apparent that the accuracy of a SIGMA = zero system is not signuficantly better than a SIGMA $=100$ meters system when the polling interval is greater than 60 seconds. Thus, if a sophisticated hardware system in terms of inherent error is installed, it requires a short polling interval to realize significant benefits.

The most strıking dıfference between the cases with inherent error equal to 0 and 100 meters and the case with inherent error equal to 1000 meters (Table 3-3) is that the interval between the minimum and maximum accuracıes is much more compact in the 100 meter case. In general, one can conclude that as the resolution in inherent error deteriorates, the system is less dependent on the remaining parameters. The accuracy figure in Table 3-3 for polling intervals of 2, 10, 60 and 120 seconds are significantly higher than the corresponding values in Tables 3-1 and 3-2, while the accuracy at a polling interval of 300 seconds is of the same order over all three Tables.

These results presenting accuracy estimates for AVM system errors can serve as a tool to be used in AVM system design.

Table 3-3. Vehicle Locatıon Accuracy at $80 \%$ Level for SIGMA $=1000$ Meters

| $T(\mathrm{sec})$ | $\mathrm{TC}(\mathrm{sec})$ | $M(\mathrm{~meters} / \mathrm{sec})$ | Accuracy (meters) |
| :---: | :---: | :---: | :---: |
| 2 | .01 | 40 | 1790 |
| 2 | .01 | 60 | 1790 |
| 2 | .1 | 40 | 1790 |
| 2 | .1 | 60 | 1790 |
| 10 | .01 | 40 | 1795 |
| 10 | .01 | 60 | 1810 |
| 60 | .01 | 40 | 1880 |
| 60 | .01 | 60 | 1950 |
| 120 | .01 | 40 | 2210 |
| 120 | .01 | 60 | 2500 |
| 300 | .01 | 40 | 2985 |
| 300 | .01 | 60 | 3500 |
| 300 | .1 | 60 | 2780 |
| 300 |  |  | 3650 |

One approach to automatically locating specified vehicles in an urban area involves the employment of proximity sensors. The proximity sensors (which may be active or passive) are distributed throughout a given area. Once installed, the position of a sensor 15 fixed. A vehicle, properly equipped, will interact with a sensor when the distance between the vehicle and the sensor is within prescribed limits. Interaction results in communzcating the identity of the vehicle and the location of the sensor to a central system. Not considered in this analysis are the proximity sensor's characteristics, the required equipment for the vehicle, or the means of communicating to the central system, This analysis presents a Markov chain model of the interaction of fixed proximity sensors with moving vehicles whose locations are to be monitored.

## A. Classıfications of Finite Markov Chains

1. Concepts and definitions. A stochastic process is any sequence of experiments amenable to probalistic analysis. A stochastic process is said to be finite if the set of possible outcomes is finite. An independent process is a finite stochastic process where knowledge of the outcome of any preceding experiment in no way affects the preduction of the outcome of the present experiment.

A finite Markov chain process is a finite stochastic process where knowledge of the outcome of the immediate past experıment does affect the prediction of the outcome of the present experiment. Furthermore, the dependence of the outcome of each experiment on the outcome of the immediately preceding experiment only is the same at each stage of successive experiments. A finite Markov chain 15 characterized by a finite set of states $\left\{s_{1}, s_{2}, \ldots ., s_{n}\right\}$. The state of a Markov chain is the outcome of the last experiment. Thus a Markov chain is in one and only one state at a given time and advances from one state to another (or remains in the same state) in accordance with a priori transition probabilities. The transition probabilıty $p_{1 j}$ is the probability that the (Markov chain) process will move from state $s_{1}$ to $s_{1}$, and $p_{i j}$ depends only on $s_{i}$. Assocrated with every ordered parr of states is a known transition probability. An $n \times n$ transition probablity matrix $P$ contains as entries the transition probabilities corresponding to each of the respective $n^{2}$ ordered pairs of states as follows:

$$
\begin{gathered}
\left.s_{1}=\begin{array}{cccc}
s_{1} & s_{2} & \cdots & s_{n} \\
s_{2} \\
\cdot \\
s_{n} & p_{11} & p_{12} & \cdots \\
p_{21} & p_{22} & \cdots & p_{2 n} \\
\cdot & \cdot & \cdots & \cdot \\
\cdot & \cdot & \cdots & \cdot \\
p_{n 1} & p_{n 2} & \cdots & p_{n n}
\end{array}\right]
\end{gathered}
$$

Each row in P comprises a probability event space such that

$$
P_{i j} \geq 0 \quad \text { for all } 1, j
$$

and

$$
\sum_{j=1}^{n} p_{\imath j}=1 \quad \text { for every } 1
$$

The transition probability matrix $P$ and an initial (startıng state completely describe a finite Markov chain process.
2. Regular Markov chains. A Markov chan is defined to be regular if and oniy if after $n$ steps (i. e., experiments) for some $n$, it is possible for the process to be in any state regardless of the starting state. The entry $p_{11}^{(n)}$ in $p^{n}$ (the $n^{\text {th }}$ power of the transition matrix) $1 s^{13}$ the probability that the process is in state $s_{j}$ after $n$ steps given that it started in state $s_{1}$. A regular Markov chan has a regular transıtıon matrix $P$ such that $P^{n}$ contaıns only positive entries (i.e., $p_{i 1}^{(n)}>0$ for all $1, j$ ). $P$ may be tested for regularity by noting whether or not the entries in $P^{2},\left(P^{2}\right)^{2},\left(P^{4}\right)^{2}, \ldots$ are positive assuming $P$ has one or more 0 entry.

Example 1. Given the following (probabllity) matrix

$P=$| $s_{1}$ |
| :---: |
| $s_{2}$ |
| $s_{4}$ |\(\left[\begin{array}{llll}s_{1} \& s_{2} \& s_{3} \& s_{4} <br>

0 \& 1 \& 0 \& 0 <br>
0.5 \& 0 \& 1 \& 0 <br>
0 \& 0 \& 0.25 \& 0 <br>
0.25\end{array}\right]\)

Successive squaring of $P, P^{2}, P^{4}, \ldots$ quickly results in large powers of $P$. When testing for regularıty, the actual values of the entries need not be determined. Denoting each positive entry by $x$ and each zero entry 0 gives

$P^{2}, P^{4}$ and $P^{8}$ are, respectively

$$
\left[\begin{array}{llll}
0 & 0 & x & 0 \\
x & x & 0 & x \\
0 & x & x & x \\
x & x & x & x
\end{array}\right],\left[\begin{array}{cccc}
0 & x & x & x \\
x & x & x & x \\
x & x & x & x \\
x & x & x & x
\end{array}\right] \text { and }\left[\begin{array}{cccc}
x & x & x & x \\
x & x & x & x \\
x & x & x & x \\
x & x & x & x
\end{array}\right]
$$

Thus $P$ is a regular transition matrix.
3. Ergodic Markov chains. A Markov chain is defined to be ergodic if and only if it is possible for the process to go from every state to every other state. Clearly a regular Markov chain is always ergodic. However, an ergodic Markov chan is not necessarily regular. That is, for every $n, P^{n}$ contains some 0 entries. However, $P^{n}$ for different values of $n$, will contan zeros in different locations. As $n$ increases, the positions of the zeros change cyclically. In this case, the chain is termed a cyclic Markov chain. Thus an ergodic Markov chain is eıther cyclic or regular but not both.

Example 2. Gıven the following transition matrix
or
, $P=\left[\begin{array}{llll}0 & x & 0 & 0 \\ x & 0 & x & 0 \\ 0 & x & 0 & x \\ 0 & 0 & x & 0\end{array}\right]$
where x denotes a positive entry. For even $\mathrm{n}>0$,

$$
P^{n}=\left[\begin{array}{llll}
x & 0 & x & 0 \\
0 & x & 0 & x \\
x & 0 & x & 0 \\
0 & x & 0 & x
\end{array}\right]
$$

For odd $\mathrm{n}>1$,

$$
\mathbf{P}^{\mathbf{n}}=\left[\begin{array}{llll}
0 & \mathrm{x} & 0 & \mathrm{x} \\
\mathrm{x} & 0 & \mathrm{x} & 0 \\
0 & \mathrm{x} & 0 & \mathrm{x} \\
\mathrm{x} & 0 & \mathrm{x} & 0
\end{array}\right]
$$

Starting in an odd-numbered state ( $s_{1}$ or $s_{3}$ ), the process is in an even-numbered state ( $s_{2}$ or $s_{4}$ ) after an odd number of steps, and in an oddnumbered state after an even number of steps.
$P$ in Example 2 is an ergodic transition matrix which is nonregular. The process characterized by $P$ is a cyclic (ergodic) chain.
4. Absorbing Markov chains. An absorbing state in a Markov chain is one which cannot be left once entered. An absorbing Markov chain is a Markov chain that has at least one absorbing state, and from every nonabsorbing state it is possible to move to an absorbing state (in one or more steps). The nonabsorbing states (of an absorbing chain) are known as transient states. The transition matrix $P$ of an absorbing chain has entries $P_{11}=1$ for each $s_{i}$ that is absorbing.

Example 3. The following transition matrix characterizes an absorbing chain

$$
P=\begin{aligned}
& s_{1} \\
& s_{2} \\
& s_{3} \\
& s_{4} \\
& s_{5}
\end{aligned}\left[\begin{array}{lllll}
s_{1} & s_{2} & s_{3} & s_{4} & s_{5} \\
1 & 0 & 0 & 0 & 0 \\
0.5 & 0 & 0.5 & 0 & 0 \\
0 & 0.5 & 0 & 0.5 & 0 \\
0 & 0 & 0.5 & 0 & 0.5 \\
0 & 0 & 0 & 0 & 1
\end{array}\right]
$$

States $s_{1}$ and $s_{5}$ are absorbing; whereas, states $s_{2}$, $s_{3}$ and $s_{4}$ are transient states.
5. Classification of states. The states of any given Markov chain can be partitioned into equivalence classes. An equivalence class comprises either an ergodic set of states.or a transient set of states. Once the process enters an ergodic set, it remains in the set. Once the process leaves a transient set, it never reenters the set.

If a chain has two or more ergodic sets of states but no transient sets, the chain in effect is a composite of two or more unrelated chans. Each of the unrelated chains consists of a single ergodic set and may be treated separately. Without any
loss in generality, every ergodic chann (regular and cyclic) consists of a single ergodic set.

An absorbing state is an ergodic set consisting of one and only one state. Such an ergodic set is referred to as a unit set. Thus an absorbing chain has one or more unit sets and one or more transient sets.

Every state of a given set whether it is ergodic or transient can "communicate" with every other state in the set. The process, however, moves toward the ergodic sets when the chain contains transient as well as ergodic sets.

## B. Propertıes of Absorbing Markov Chains

1. Canonical Form of $P$ and $P^{n}$. The transition matrix $P$ of an absorbing chain can always be arranged to have the following canonical form (by relabelıng states)

$$
P=\left[\begin{array}{l|l}
I & 0 \\
\hline R & Q
\end{array}\right]
$$

The submatrix $I$ is an $\ell \times \ell$ identity matrix whose entries are the transition probabilities for every ordered pair of absorbing states ( $s_{1}, s_{j}$ ) where

$$
p_{i j}=\left\{\begin{array}{l}
0 \text { ififj } \\
1 \text { ifi=j }
\end{array}\right.
$$

The submatrix $Q$ is an $m \times m$ matrix whose entries are the transition probabilities for every ordered pair of transient states. The submatrix $R$ is an $\mathrm{m} \times \ell$ matrix whose entries are the transition probabilities for every ordered parr of states ( $s_{1}, s_{j}$ ) where $s_{1}$ is a transient state and $s_{j}$ is an absorbing state. The submatrix 0 is an $\ell \mathrm{x} m$ matrix whose entries are zeros corresponding to the zero transition probabilities of moving from any absorbing state to any transient state. Powers of $P$ have the canonical form

$$
P^{n}=\left[\begin{array}{c|c}
I & 0 \\
\hline M & Q^{n}
\end{array}\right]
$$

where

$$
M=\left[I+Q \div Q^{2}+\cdots+Q^{n-1}\right] R
$$

Note that the expression for Mis a matrix equation.

Theorem 1. In any finite Markov chain, regardiess of the initual (starting) state, the probability that the process is in ergodic state after $n$ steps approaches 1 as $n$ approaches ınfinity. (A proof of Theorem 1 appears in Ref. 1.)

A Corrolary to Theorem 1 is that are real numbers $b$ and $c$ where $b>0$ and $0<c<1$ such that $p_{i j}^{(n)} \leq b c^{n}$
for any ordered pair of transient states ( $s_{1}, s_{j}$ ). This gives the rate at which $p_{i j}^{(n)}$ approaches 0 .

Every entry in $Q^{n}$ in the canonical form of $P^{n}$ of an absorbing chain approaches 0 as $n$ increases without limit.
2. Fundamental matrix. The fundamental matrix of an absorbing chain $1 s$ defined as

$$
\begin{equation*}
N=[I-Q]^{-1} \tag{l}
\end{equation*}
$$

Note that

$$
\frac{I}{I-Q}-\frac{Q^{n}}{I-Q}=I+Q+Q^{2}+\cdots+Q^{n-1}
$$

and since $Q \neq I$ and $\lim _{n \rightarrow \infty} Q^{n}=0$

$$
[I-Q]^{-1}=\lim _{n \rightarrow \infty}\left[I+Q+Q^{2}+\cdots+Q^{n-1}\right]
$$

the inverse of $I-Q(1 . e, N)$ always exists.
The submatrix $M$ in $P^{n}$ as $n$ approaches infinity may be expressed as

$$
\begin{equation*}
M=[I-Q]^{-1} R=N R \tag{2}
\end{equation*}
$$

The fundamental matrix N has the following probabilistic interpretation.

Let $u_{i}(\mathrm{k})=1$ if the process starts in transient state $s_{1}$ ahd 15 in transient state $s_{j}$ after $k$ moves. Otherwise $u(k)=0$. Let $t_{i]}^{(n)}$ denote the number of times the process is in transient state $s$, starting and during $n$ moves given that it started in transient state $s_{1}$. Thus

$$
t_{i j}^{(n)}=u_{i j}^{(0)}+u_{i j}^{(1)}+\cdots+u_{i j}^{(n)}
$$

The probability that the process is in transient state $s_{j}$ after the $k^{\text {th }}$ move is

$$
p\left(u_{2 J}^{(k)}=1\right)=q_{i J}^{(k)}
$$

given that $s_{1}$ is transient and the starting state. The mean of $u_{1 j}^{(k)}$ is

$$
m\left(u_{i j}^{(k)}=1 \cdot q_{i j}^{(k)}+0 \cdot\left(1-q_{i j}^{(k)}=q_{i j}^{(k)}\right.\right.
$$

The mean of $t_{1 j}^{(n)}$ is

$$
m\left(t_{i j}^{(n)}\right)=q_{i j}^{(0)}+q_{i j}^{(1)}+\cdots q_{i j}^{(n)}
$$

the $1,3^{\text {th }}$ entry of

$$
Q^{(0)}+Q^{(1)}+\cdots Q^{(n)}
$$

where $Q^{(0)}=I$.

## Then

$$
n_{i j}=\lim _{n \rightarrow \infty} m\left(t_{l j}^{(n)}\right)
$$

1s the $1, j^{\text {th }}$ entry of the fundamental matrix expressed in (1). The value of $n_{1 j}$ is the mean number of times the chain is in transient state $s$ given that it started in transient state $s_{1}$ and continues until the process is absorbed (1. e., reaches an absorbing state).
3. Statistics on the number of times the process isin a transient state. Let $v_{1}$ denote the number of steps (including the original position) before absorption, given the starting state is $s_{1}$. If $5_{1}$ is in an absorbing state, then $v_{1}=0$. Given that the absorbing chain contans a transient set denoted by $T$, and $s_{1}$ is a transient state if and only if $s_{1} E T$ (1.e., $s_{1}$ "is a member of" $T$ ). Then

$$
\begin{equation*}
m\left(v_{i}\right)=\sum_{s_{j} \varepsilon T} n_{i, j} \tag{3}
\end{equation*}
$$

which is the $1^{\text {th }}$ row sum of the fundamental matrix $N$. Each row sum of $N$ appears in the $m \times 1$ column vector

$$
\begin{equation*}
\alpha=\mathrm{NC} \tag{4}
\end{equation*}
$$

where Cis a mxl column vector whose entries are all l's.

The variance of the function $v_{1}$ is

$$
\operatorname{var}\left(v_{1}\right)=m\left(v_{1}^{2}\right)-\left(m\left(v_{1}\right)\right)^{2}
$$

where

$$
m\left(\dot{v}_{i}^{2}\right)=\sum_{s_{j} \neq T} p_{i j} \cdot 1+\sum_{s_{j} \varepsilon T} p_{i j} m\left[\left(v_{1}+1\right)^{2}\right]
$$

(Notethat the original position is necessarily included in the expression for $m\left(v_{1}^{2}\right)$.)

Contınuing,



$$
=\sum_{s_{j} \varepsilon T} p_{1 j}\left[m\left(v_{z}^{2}\right)+2 m\left(v_{i}\right)\right]+1
$$

$$
\left\{m\left(v_{I}{ }^{2}\right)\right\}=\left\{\sum_{s_{j} \varepsilon T} p_{i j}\left[m\left(v_{1}{ }^{2}\right)+2 m\left(v_{i}\right)\right]+1\right\}
$$

The braces denote a column vector where each entry corresponds to a different value of 1 .

Therefore,

$$
\begin{aligned}
& \left\{m\left(v_{1}^{2}\right)\right\}=Q\left\{\mathrm{~m}\left(\mathrm{v}_{\mathrm{i}}^{2}\right)\right\}+2 Q \alpha+\mathrm{C} \\
& {[I-Q]\left\{\mathrm{m}\left(\mathrm{v}_{2}^{2}\right)\right\}} \\
& \begin{aligned}
\left\{\mathrm{m}\left(\mathrm{v}_{\mathrm{i}}^{2}\right)\right\} & =[I-Q]^{-1}[2 Q \alpha+\mathrm{C}] \\
& =2 \mathrm{NQ} \alpha+\mathrm{NC} \\
& =2 \mathrm{NQ} \alpha+\alpha
\end{aligned}
\end{aligned}
$$

Since

$$
\begin{aligned}
& N=\frac{I}{I-Q} \\
& N-N Q=I \quad \text { and } \quad N Q=N-I
\end{aligned}
$$

and

$$
\begin{aligned}
\left\{\operatorname{m}\left(v_{i}^{2}\right)\right\} & =2[N-I] \alpha+\alpha \\
& =[2 N-I] \alpha
\end{aligned}
$$

Finally, the variance of $v_{1}$ for each 1 expressed as entries in $m \times 1$ column vector is

$$
\begin{aligned}
\left\{\operatorname{var}\left(v_{i}\right)\right\} & =\left\{m\left(v_{i}^{2}\right)-\left(m\left(v_{i}\right)\right)^{2}\right\} \\
& =[2 \mathbb{N}-I] \alpha-\alpha_{s q}
\end{aligned}
$$

where $\alpha_{s q}$ results from squaring each entry $m\left(v_{1}\right)$ in $\alpha$ shown in (4).

Example 4. A partıcle moves a unit distance along a straight line. Given that it is in $s_{i}$, it moves to $s_{1+1}$, one unit to the right, with probability 0.5 , or to state $s_{1-1}$, one unit to the left, with probability 0.5. Two states are introduced, one at each end of the line, to serve as barriers, These are absorbing states such that the process is absorbed if it reaches either absorbing state. Assume there are five states where $s_{1}$ and $\mathbf{s}_{5}$ are absorbing, and $s_{2}, s_{3}$, and $s_{4}$ are transient. The probability matrix appears in Example 3. Reordering the rows and columns gives the following canonical form:

$P=$| $s_{1}$ |
| :---: |
| $s_{5}$ |
| $s_{2}$ |
| $s_{3}$ |
| $s_{4}$ |\(\left[\begin{array}{lllll}s_{1} \& s_{5} \& s_{2} \& s_{3} \& s_{4} <br>

0 \& 0 \& 0 \& 0 \& 0 <br>
0 \& 1 \& 0 \& 0 \& 0 <br>
0.5 \& 0 \& 0 \& 0.5 \& 0 <br>
0 \& 0 \& 0.5 \& 0 \& 0.5 <br>
0.5 \& 0 \& 0.5 \& 0\end{array}\right]\)

$$
\mathrm{N}=[I-Q]^{-1}=s_{2} s_{3}\left[\begin{array}{lll}
s_{2} & s_{3} & s_{4} \\
s_{4}
\end{array}\left[\begin{array}{lll}
1.5 & 1 & 0.5 \\
1 & 2 & 1 \\
0.5 & 1 & 1.5
\end{array}\right]\right.
$$

Thus, for example, of the process starts in state $s_{2}$, the mean number of time it is in state $s_{2}, s_{3}$ and $s_{4}$ is $1.5,1$ and 0.5 , respectively.

Furthermore,

since

$$
\lim _{n \rightarrow \infty} Q^{n}=0
$$

and

$$
\lim _{n \rightarrow \infty} M=N R
$$

as shown in (1) and (2).
In example 4

and

$$
\begin{gathered}
s_{2} \\
s_{3} \\
s_{4}
\end{gathered}\left[\begin{array}{cc}
s_{1} & s_{5} \\
0.75 & 0.25 \\
0.5 & 0.5 \\
0.25 & 0.75
\end{array}\right]
$$

Hence, for example, if the process starts in state $s_{2}$, it will be absorbed in state $s_{1}$ with probability 0.75 or in state $s_{5}$ with probability 0.25 . The row sums of NR are necessarily 1 in accordance with Theorem 1. The mean number of steps before absorption including the original position for each transient starting state appears in $\alpha$ as shown in (4).


The mean number of steps before absorption is 3 if the process starts in $s_{2}$ or $s_{4}$; whereas, it is 4 if the process starts in $s_{4}$.

The variance of the number of steps (including the original position) before absorption for each starting state appears in the column vector

$$
[2 N-I] \alpha-\alpha_{s q}
$$

from expression (5). In example (4)
$2 \mathrm{~N}-\mathrm{I}=\left[\begin{array}{lll}2 & 2 & 1 \\ 2 & 3 & 2 \\ 1 & 2 & 2\end{array}\right], \alpha=\left[\begin{array}{l}3 \\ 4 \\ 3\end{array}\right]$ and $\alpha_{\mathrm{sq}}=\left[\begin{array}{r}9 \\ 16 \\ 9\end{array}\right]$
Thus

$$
[2 N-I] \alpha-\alpha_{s q}=s_{3}\left[\begin{array}{l}
s_{2} \\
s_{4}
\end{array}\right]
$$

The mean number of steps before absorption is greatest for starting at $\$_{3}$. However, the varıance is the same for each starting transient state. (Note that when the variances are quite large compared to the corresponding entries in $\alpha_{s q}$, it indicates that the means are unreliable estimates for that particular chain.)

## C. Model of Absorbing Markov Chan for Class II and IV Systems

Consider a portion of an area to be monitored as shown in Fig. 3-5. Subareas are $5 \times 5$ square blocks, and each subarea has an identical sensor layout. A (monitored) vehicle entering a sensed intersection corresponds to an absorbing state. This is to be interpreted as updated information as to the vehucle's location. When the process is in an absorbing state, the location of the monitored vehicle is known (to within the detection radius of the sensor). A vehicle entering an unsensed intersection corresponds to a transient state. The absorbing Markov chain models a sequence of experiments for locating a vehicle to within prescribed limits of accuracy.

Given that a vehicle starts at any given intersection (sensed or unsensed), what is the mean and variance of the number of blocks the vehicle moves until being sensed? Once the vehucle is sensed, a new experiment begins. Thus, between sensings, an uncertanty exists as to the vehicle's location. This is reflected in the magnitude of the mean and variance of the number of blocks the vehicle moves between sensings.


Fig. 3-5. Urban Distribution Pattern for Monitored Proximity Sensors

The number of sensors, their layout, and transition probabilities between orthogonally adjacent intersections is required a priori information. Unıformity of deployment of sensors assumes unbiased routes. Random movement of the vehicle corresponds to unbiased routing through the sensed area. Thus the direction of travel of a vehicle from an intersection will be in any one of four possible directions with equal probabılity.

If one were to incorporate a different transition probabllity for each of the four possible directions, the number of states in the Markov chain model would increase fourfold. Each state would be assocrated with a pair of labels. The intersection entered would be designated by one label and the direction from which it was entered by the other. Such a transition matrix would be meaningful if the transition probabılities were accurately known. That 15 , the probability that a vehicle upon leaving a particular intersection will go straight, make a left turn, a right turn or a U-turn is a priori information. Without this information, equiprobable direction of travel (to any of the four adjacent intersections) is ássumed. The resulting statistical accuracy establishes achievable bounds on the system's accuracy.

Returning to Fig. 3-5, only the subarea with labeled intersections need be considered. Boundary intersections (of the subarea) act as reflecting boundaries in the Markov chain model. A vehicle in intersection 1 corresponds to the process being in transient state 1. The transıtion probability from state 1 to the intersection due North is 0.25 . Since that intersection has the same relative location in its subarea as does intersection $F$ in the subarea under discussion, an upward move (due North) is equivalent to a reflection to intersection $F$. Identical sensor layouts for all subareas is clearly required. This permits the use of a small transition matrix ( $25 \times 25 \mathrm{in}$ Fig. 3-5) for a Markov chain model of an enture area where fringe effects are neglected. Intersections labeled with characters are sensed and are associated with absorbing states. Unsensed intersections are labeled with numbers and are associated with transient states. The reflection properties of transient boundary intersections are apparent in the
submatrices $Q$ and $R$ in Figs. 3-6 and 3-7, respectively. (Note that states $s_{1}$ and $s_{4}$ are reflecting boundaries in Example 2.)

The matrix N and column vectors $\alpha=\mathrm{NC}$ and [2N - I] $\alpha-\alpha_{\text {sq }}$ were computed on an IBM $360 / 65$. The components of $\alpha$ and $\alpha_{\text {sq }}$ rounded to 3 decimal places are:

| 1 | 1.667 |  | 2.778 |
| :---: | :---: | :---: | :---: |
| 2 | 2.667 |  | 7.111 |
| 3 | 1.667 |  | 2.778 |
| 4 | 1.667 |  | 2.778 |
| 5 | 1.667 |  | 2.778 |
| 6 | 1.667 |  | 2.778 |
| 7 | 2.667 |  | 7.111 |
| $\alpha=\mathrm{NC}=8$ | 1.667 | $\alpha_{s q}=$ | 2.778 |
| 9 | 1.667 |  | 2.778 |
| 10 | 2.667 |  | 7.111 |
| 17 | 1.667 |  | 2.778 |
| 12 | 1.667 |  | 2.778 |
| 13 | 1.667 |  | 2.778 |
| 14 | 1.667 |  | 2.778 |
| 15 | 2.667 |  | 7.111 |
| 16 | 1.667 |  | 2.778 |


|  | 2 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11. | 12 | 13 | 14 | 15 | 16 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | . 25 | 0 | 25 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | . 25 | 0 | 0 | 0 | 0 |
| 3 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | . 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 25 | 25 | 0 | 25 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 25 | 0 | 25 | 25 | 0 | 0 | 0 | 25 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $0$ | 25 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | .25 | 0 |
| 15 | 0 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | . 25 | 0 | 25 | 0 | 25 |
| 26 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 0 |

Fig. 3-6. Submatrix $Q$ of Absorbing Chain Model for Monitored Subarea in Fig. 3-5

|  | A | B | C | D | E | F | G | H | J |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | . 25 | 0 | . 25 | 0 | 0 | . 25 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | . 25 | 0 | . 25 | 0 | 0 | . 25 | 0 | 0 |
| 4 | . 25 | 0 | . 25 | . 25 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | . 25 | . 25 | . 25 | 0 | 0 | 0 | 0 |
| 6 | 0 | . 25 | . 25 | . 25 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | . 25 | 0 | . 25 | . 25 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | . 25 | . 25 | 0 | . 25 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11. | 0 | 0 | 0 | 0 | 0 | . 25 | . 25 | . 25 | 0 |
| 12 | 0 | 0 | 0 | 0 | . 25 | . 25 | . 25 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 | . 25 | . 25 | 0 | . 25 |
| 14 | 0 | 0 | . 25 | 0 | 0 | . 25 | 0 | . 25 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 0 | 0 | 0 | . 25 | 0 | 0 | . 25 | 0 | . 25 |

Fig. 3-7. Submatrix $R$ of Absorbing Chaın Model for Monitored Subarea in Fig. 3-5

Thus, starting in a transient state or an unsensed intersection, the mean number of blocks a vehicle moves before being sensed is 1.667 or 2.667. The variance of the number of moves for each starting state ( 1 through 16) is 1.778 which are the entries of

$$
[2 N-I] \alpha-\alpha_{s q}
$$

Since 1.778 is a fraction of 2.778 and 7.111 (the distinct entries of $\alpha_{\text {Sq }}$ ), the means given in $\alpha$ are reliable estimates for the layout in Fig. 3-5.

Note that the probability of being sensed cannot be computed. The probability of beang sensed by a sensor in the same relative location as say $B$ (Northeast corner of a subarea) can be determined from NR. See Example 4.

The ratio of sensed intersections to the total number of intersections in a monitored area is of interest. In Fig. 3-5, 4 sensors are each sharing 4 subareas. These are sensors at intersections A, $B, H$ and $J$. Thus the total number of sensors per subarea for 5 (Interior) +4 (each shared by 4 subareas)/4 or 6. The total number of intersections per subarea is 9 (interior) $\div 4$ (each shared by 4 subareas) $/ 4+12$ (each shared by 2 subareas) $/ 2$ or 16. Thus the ratio of sensed intersections to total inter sections is $3 / 8$.


Fig. 3-8. Monitored Subarea with Sensor Density of 3/9

Consider a monitored area with identical subareas as shown in Fig. 3-8 where the ratio of sensed intersections to total intersections is $3 / 9$. Its associated submatrices $Q$ and $R$ appear in Figs. 3-9 and 3-10, respectively. For completeness the fundamental matrix $N=[I-Q]^{-1}$ corresponding to Fig. 3-8 appears in Fig. 3-11. The entries are rounded off to 3 decımal places.

The mean and variance of the number of blocks a vehicle moves before detection starting from each of the unsensed intersections is 2 and 2 , respectively.
1
1
2
3
4
5
6
7
7
8
9 $\left[\begin{array}{cccccccccc}10 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\ 0 & .25 & 0 & 0 & 0 & 0 & .25 & 0 & 0 & 0 \\ 0 & 0 & 0 & .25 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & .25 & 0 & .25 & 0 & 0 & 0 & 0 \\ 0 & 0 & .25 & 0 & 0 & 0 & .25 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & .25 & 0 & .25 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & .25 & 0 & 0 & .25 \\ 0 & 0 & 0 & 0 & 0 & .25 & 0\end{array}\right]$

Fig. 3-9. Submatrix $Q$ of Absorbing Chain Model for Monitored Subarea in

Fig. 3-8
$c$
1
2
3
4
5
6
7
8
9 $\left[\begin{array}{cccccc}A & B & C & D & E & F \\ .25 & 0 & .25 & 0 & 0 & 0 \\ 0 & .25 & 0 & .25 & 0 & 0 \\ .25 & 0 & .25 & 0 & 0 & 0 \\ 0 & 0 & .25 & .25 & 0 & 0 \\ 0 & .25 & .25 & 0 & 0 & 0 \\ 0 & 0 & 0 & .25 & .25 & 0 \\ 0 & 0 & .25 & .25 & 0 & 0 \\ 0 & 0 & 0 & .25 & 0 & .25 \\ 0 & 0 & .25 & 0 & .25 & 0 \\ 0 & 0 & .25 & 0 & .25\end{array}\right]$

Fig. 3-10. Submatrix $R$ of Absorbing Chan Model for Monitored Subarea in Fig. 3-8


FIG 7 The Fundarented Matrix in Corresponding to Fig 4

Fig. 3-11. Fundamental Matrix $N$ Corresponding to Fig. 3-8

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# PART FOUR: <br> AM BROADCAST AND BURIED <br> LOOP FEASIBILITY ANALYSES <br> FOR AVM USE 

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## I. VEHICLE LOCATION BY MEANS OF AM BROADCASTING STATION CARRIER SIGNALS:-

Carrier signals of commercial AM broadcasting stations can be used as the source of vehicle location information. : As in well-known navigation systems, the signals radiating from pairs of stations will form an hyperbolic grid or coordinate system, and vehicles which are equipped with phase-lock receivers and phase repetition counters can keep track of the location of the vehicle in this hyperbolic coordinate grid. This information is then periodically transmitted to a central command base where the transformation from hyperbolic to geographic coordmates is performed, and the actual location of the vehicle is determined and displayed.

## A. Introduction

Most vehicle location and navigation systems require dedicated transmitter-receiving equipment combinations and frequency allocations for the location function. A particular advantage of the AM broadcast phase-difference monitoring system is that commercial station signals ( 0.53 to 1.60 MHz ) are used to furnish the vehicle location information. Therefore, neither dedicated transmitters nor special frequency allocations are required.

Carrier signals from thr ee AM stations located near the urban perimeter are used to form a coordinate system of hyperbolas of constant phase difference between the signals from pairs of stations (Fig. 4-1). Therefore, this vehicle location technique shares many of the characteristics of other hyperbolic navigation methods such as OMEGA, LORAN, and particularly DECCA. In this location method, however, the transmission frequencies from the AM stations need not be synchronized, in contrast to the established navigation systems. It $1 s$ more akin to the differential versions of the foregoing systems. In the differential verisons, mobile location equipment is utilized at fixed geographical sites for the purpose of improving the location accuracy of vehicles in the neighborhood by determining the signal phase or delay variance at the known site from that predicted, and this variance is used to correct the location data received by the vehicle.

The AM broadcast vehicle location technique relies on a frequency transformation method whereby the several frequencies of three AM broadcasting stations are separately normalized to a common frequency, and the relative phases of these common frequencies are compared to provide hyperbolic lines of position. An exact integral relationship between the carrier frequencies of the AM stations is not required, although harmonically related frequencies would result in a stationary "virtual hyperbolic pattern" and would somewhat simplify the location process.

Vehicular equipment consists of at least three phase-locked loop recesvers to extract the carrier

[^3]

Fig. 4-1. Zero Degree Phase Difference Hyperbolic Contours Produced by Pair of Synchronized RF Signals
frequencies and also a second set of three phaselocked loop frequency multipliers to generate the common frequency. Phase comparators and digital counters are used to keep track of the vehicle location within the "virtual hyperbolic pattern." The hyperbolic coordinates are stored for subsequent transmission to a central command and control base.

Central equipment required consists of a limited arithmetic processor or table look-up computer which is needed to relate the hyperbolic pattern coordinate information to an actual geographical location

## B. Hyperbolic Location Principles

If two separated and synchronized sources of radiation transmit signals in an isotropic medium, a receiver positioned midway between them, or on the locus of points which is equidistant from each transmitter, will detect no difference in the time-of-arrival or the phase of the signals from the separate sources. The locus is the perpendicular bisector of the connective between the two sources. (See Fig. 4-1.)

If the receiver is at one side or the other of the bisector, the signal from the nearer transmitter will arrive at some finite amount of time before the signal from the farther source. If the signals are continuously transmitted, the phase of the nearer wall lead the phase of the farther. Another locus of constant time or phase difference can be generated by maintaining the same difference in distance from the recelver to each transmitter. The curves for constant time or phase difference will be confocal hyperbolas that are symmetric around the bisector (see Fig. 4-1).

A line-of-position (LOP) can be determined relative to a pair of RF transmitters by noting the time difference in the arrival of the signals, which corresponds to one of the hyperbolas. There will be ambiguity as to which branch of the hyperbola represents the true LOP. If the signals are continuous wave and only the phase differences are determined, the degree of $L O P$ ambiguity increases many-fold since the phase pattern is repeated whenever the cumulative distance change to the two transmitters equals one wavelength. The resolution of the ambiguity is described later.

If the two stations are transmitting on slightly different frequencies, the relative phase between the carriers will change cyclucally at a rate determined by the difference in frequency. This rate will be the same anywhere that the two signals can be recerved. If the locus of lines of constant phase difference are now considered, they again comprise a family of confocal hyperbolas, but instead of being stationary, they will sweep through the area covered by the two stations (Fig. 4-2). The hyperbolas, as a function of time, will tend to


Fig. 4-2. Apparent Motion of Hyperbolas Due to Slight Difference in Two Signal Frequencies
form acutely around the station radiating the higher frequency and then move toward the lower frequency station; straightening as they reach the midpoint, then curving around the lower frequency station and then vanishing on the extension of the line joining the stations. A recenver capable of counting the passage of hyperbolas representing a particular phase difference will accumulate the same count in the same time interval regardless of the location within the service area of the two stations.

If the constant-phase difference counting receiver is positioned in a stationary hyperbolic field, no counts will be accumulated as long as the receiver's location is fixed. If the receiver is moved in such a manner as to cause the difference in the distances to the two stations to change by one wavelength, then one count will be accumulated. Similarly, in a moving field, a one-unit difference in counts will be accumulated by a stationary receiver as compared to a recelver that is moved by a wavelength distance difference.

The AVM system based on AM broadcast signals is discrete as opposed to continuous location systems in that the intersections of hyperbolas form a grid which can be transformed into specific urban area locations corresponding to these intersections. Interpolation between grid lines is not used. Therefore it is somewhat like a proximity system with the hyperbolic intersections taking the place of physical devices or signposts located at intersections or at fixed points. Continuous systems provide somewhat uniform coverage of the service area and allow any geographical locations within this area to be determined to some limiting precision dictated by the technique. The grid described by the intersection of the hyperbolas allows the actual geographical location of the vehicle to be somewhere within the hyperbolic triangle described by the coordinates of a particular triad vertex. The dimensions of this triangle are a function of the distance to the foci of the two families of hyperbolas and also of the wavelength of the common frequency. In most continuous AVM systems, the precision diminishes with the distance from the fiducial points. In the AM Broadcast hyperbolic AVM system, the location precision can be adjusted in the princapal service area by the choice of the common frequency.

Established navigation systems such as OMEGA, LORAN, and DECCA refer to the areas between adjacent hyperbolas of constant phase as lanes. These navigation lanes vary in width from 1.5 to 15 km , depending on the frequency used in the system, and the principal goal of these methods is to mantain a vehicle's location precisely within a selected lane. In contrast, the AM broadcast vehicle location method utilizes much narrower (e.g., 0.15 km ) lanes and keeps track only of the ID number of the hyperbola of constant phase difference that the vehicle has crossed and in which direction the hyperbola was traversed. Therefore, the location precision is a function of the lane width and will vary with the distance from the AM station pair. This system is intended for use in metropolitan areas and adjacent suburbs of rather limited size compared to the much larger service areas of navigation systems. Since AM transmitting sates are usually located near the outskirts of the area they serve, the divergence of the hyperbolas and the consequent loss in location precision can be held to reasonable values.

In many prior studies and developments concerned with emergency vehicle location problems (see Brbliography), a general goal has been to provide a location capability to one city block, or roughly 0.16 km ( 0.1 mile). Lane widths of this size can be generated with a frequency of 1 MHz .

In order to generate a hyperbolic coordinate system from AM station signals, these signals must be transformed to a common frequency which is phase coherent to the AM carrier. To be useful without restrants requires that this common frequency be a multiple of the highest common divisor of the avallable AM carriers. The common frequency should therefore be a multiple of 10 kHz .

The individual AM carrier signals are recerved by the vehicle recelvers, and the se signals in turn are each used to separately synthesize the common frequency. The common frequencies are therefore phase-coherent with the original AM carriers and effectively change the radiation from each of the AM stations to the common frequency. A virtual hyperbolic pattern is generated from each pair of AM stations recelved; and if the AM signals were phase coherent, the pattern will be stationary in space. It is then only necessary to measure the phase differences and count the number of times the phase pattern has repeated as the vehicle travels in order to determine a new location from a known starting point. Three pairs of signals (three station) are sufficient to remove any ambiguity in the determination of the new location from the old location (Fig. 4-3). Since the


Fig. 4-3. Change in Receiver Location from Hyperbolic Area 5-9-5 to 10-2-7
spacing of the hyperbolic patterns is a function of the distance from the station pair, the relationship between the phase pattern counts and actual distances traveled would have to be computed. In thas AVM system, the computational abılity need not be
placed in each vehicle. The computation of locations is reserved for the central command base where the location information is desired.

It is immaterial whether the hyperbolic grid pattern is fixed or moving as far as the location process is concerned. If fuxed, then only the counts accumulated by moving recelvers are necessary to determine the new positions from the old. If the grid is moving, then the difference in counts between the moving recelvers and a stationary receiver is all that is required. Besides the magnitude of the counts, it is also necessary to know the "direction" of passage of the hyperbola of constant phase difference. The hyperbolas always move from the higher frequency source toward the lower frequency. If the hyperbolas are stationary, the vehicle's movement toward one source will tend to increase the apparent frequency from that source whale decreasing the frequency of the other. Therefore an assignment can be made as to which direction is to be called a positive count and which a negative count.

## C. Vehicle Equipment Requirements

A block diagram of one of the recervers to be installed in the vehicles is shown in Fig. 4-4.


Fig. 4-4. Phase-Locked Loop AM Recexver on Vehicle for Hyperbolic AVM Technique

Three of these receivers are required for each vehicle. A conventional RF amplifier is used to provide selectivity and gain of the desired AM signal applied to the phase detector of the phase-lock loop (PLL). The voltage-controlled oscillator frequency in the PLL is adjusted to run at the same frequency as the AM station carrier. The oscillator output is divided by a variable modulus counter (-53 to 160) so as to produce an output frequency of 10 kHz . The 10 kHz signal is applied to a flipflop which provides a square-wave of 5 kHz used as the reference input to the phase detector of the frequency multiplying PLL. A 1 MHz voltagecontrolled crystal oscillator is phase-locked to the 5 kHz reference by dividing the oscillator frequency by 200 to produce a second 5 kHz signal which is compared to the reference. Therefore, the 1 MHz signal 15 phase-locked to the AM carrier frequency so that the phase relationship between the 1 MHz and the carrier is repeated at least every 53 to 160 cycles of the AM carrier.

Three such receivers, each tuned to a different AM station, will produce three separate 1 MFIz
signals, each phase-coherent with the appropriate AM carrier.

The problem then remains to determine the ID number and direction of the hyperbola that 15 either traversing or being traversed by the vehicle. As stated previously, the measurement of the frequency difference and the determination of which is the greater frequency are required. The technique selected to determine the frequency difference and also to yield information as to which is the higher or lower frequency is to use an up-down counter in which one frequency provides incrementing pulses and the other decrementing pulses. The state of the counter should then indicate the integrated frequency difference between the two frequencies which is the algebraic sum of the hyperbola of constant phase difference traversed.

The up-down counter must respond to every ancrementing and decrementing pulse because any pulse missed will displace the measured location by one unit in the hyperbolic grid. In order to prevent the uncertainty in the up-down counter which could be caused by the samultaneous arrival of up and down pulses, resynchronization of the 1 MHz pulses was required. A synchronizing frequency at least four times the frequency to be counted is required to assure that no pulse $1 s$ lost or split. The logic for resynchronizing to 4.192 MHz is shown in Fig. 4-5. The $\log _{10}$ discards both incrementing and decrementing pulses which are inputs to the same up-down counter and arrive in the same synchronizing interval.


Fig. 4-5. Up-Down Counters Sync Logic for Hyperbolic AVM Technique

Each of the three counters in the receiver maintains a count which is the integrated algebraic sum of the apparent frequency difference between a pair of AM stations each nominally radiating at the common frequency. Part of this frequency difference is due to the AM stations not being phase coherent
(1. e., not exactly on the assigned frequency) and part is due to vehicular motion.

## D. Vehicle Location Method

If three $A M$ stations, $A, B$, and $C$, are monitored (Fig. 4-3) and the transformation of the carriers yields three common frequencies $f_{a}, f_{b}$, and $\mathrm{f}_{\mathrm{c}}$, then the three counters in the vehicles will accumulate counts N in a time t in accordance with:

$$
\begin{array}{r}
N_{a}=\left(f_{a}-f_{b}\right) t+V_{a b}(f) t \times F(x, y)-C \\
N_{b}=\left(f_{b}-f_{c}\right) t+V_{b c}(f) t \times G(x, y)-C \\
N_{c}=\left(f_{c}-f_{a}\right) t+V_{c a}(f) t \times H(x, y)-C \\
C=3 \times 10^{9} \mathrm{~m} / \mathrm{sec}
\end{array}
$$

where $f$ is the common frequency, $V$ is the vehicle velocity component parallel to the baseline of the station pair, and $F, G$, and $H$ are general equations of the second degree (describing the three families of hyperbolas) in terms of $X$ and $Y$ which are the geographical location of the vehicle in an arbitrary orthogonal coordinate system. This system of equations does not yield an explicit analytic solution for the location in terms of $X$ and $Y$. It does indicate the separability of the counts due to slight differences on the common frequency and the counts caused by vehicle motion. Counting is negligibly influenced by the difference in frequency of $f_{a}, f_{b}$, or $f_{c}$.

At the base, the location process is initialized by first receiving the actual geographical location (in $X$ and $Y$ ) of the vehicle and the initial content of the three counters (called $\mathrm{N}_{\mathrm{aI}}, \mathrm{N}_{\mathrm{b} 1}$, and $\mathrm{N}_{\mathrm{cI}}$, respectively). The coordinates in X and $Y$ and the counter states are stored. The counter states of the stationary recelver are also stored at the same instant. An explicit calculation 15 then made using the X-Y location and the coordinates of the AM stations which yield the location of the vehicle in terms of the parametric families of the hyperbolas. Each hyperbola in each family is numbered, and the results of this calculation give the location in three integers which represent the nearest hyperbola of each family.

Subsequent locations are determined by receiving the current state of the three counters from the vehicle. First, the initial state of the vehicle counters is subtracted from the current state, and second, the change in the state of the stationary receiver counters (from the initializing time to the current time) is determined and subtracted to yield the change in each of the hyperbolic coordinates caused by vehicle motion. The new X-Y coordinates of the vehicle location are then calculated with an iterative least-squares algorithm. The algorithm uses the old X-Y location and develops the required changes in $X$ and $Y$ so that the calculated new position will have the same hyperbolic coordinates as those determined for the vehicle from the current counter states. This method was chosen over an analytic technique as it yields a "most likely" solution in less time than an analytic method which has the additional disadvantage of having several pairs of coordinates as solutions.

Only two of the three avalable hyperbolic coordinates are necessary in all of the calculations
as the third coordinate is not independent. The third coordinate does provide a check in that the sum of the hyperbolic coordinates should be a constant plus or minus one. Additionally, for locations near the vertex (the one AM station common to each hyperbolic family), the algorithm may become divergent and another set of coordinates should be used.

## E. Accuracy Analysis

All AM broadcast stations in the United States operate on assigned carrier frequencies which are multiples of 10 kHz in the frequency region between 530 and 1600 kHz . The FCC requires that the actual carrier frequency be wathin 20 Hz of the assagned frequency. If all the AM stations within a gaven geographical area were exactly on the assigned frequency, the relationship between any two stations could be expressed as:
(1) $f_{1} / f_{2}=(n+p) / n$, where $n$ and $p$ are
both integers.
The carriers could be said to be phase-coherent in that the phase relationships between the two carriers are repeated every $n+p$ cycles for one carrier and every $n$ cycles for the other. If this condition $1 s$ maintained, it is then possible to synthesize another frequency, which is also a multiple of 10 kHz which is phase-coherent to each of the carriexs within the area.

The 10 kHz can be multiplied to another frequency, say 1 MHz , which will be phased coherent with the original carrier. Since the FCC allows a frequency tolerance of 20 Hz , the synthesized 1 MHz signal will have a tolerance of:
(2) $\pm \mathrm{XHz}= \pm 20 \mathrm{~Hz}\left(10^{6} \mathrm{~Hz}\right) / \mathrm{fHz}$, where $f$ is the $A M$ carrier frequency.

Therefore $X$ can vary between 39 and 12 Hz , depending upon the frequency of the AM broadcasting carrier. It is therefore possible that a pair of AM stations could cause a beat frequency between the two "normalized" carriers approaching 80 Hz . The impact of the frequency difference is principally upon the equipment design, the sampling rate for location purposes, and the amount of information that must be transmitted from the vehicle. These effects wall be discussed later.

A secondary effect of the AM carrier being off frequency and ther eby causing the 1 MHz to be slightly off is that the location process will be reduced in precision. A wavelength of the actual frequency will be slightly shorter or longer than expected by up to 39 parts per million. This error would be on the order of 1 meter on the baseline connecting a station pair with a separation of 30 km and up to 2 meters some 60 km away from either station and therefore negligible.

## F. System Data Requirements and Polling Intervals

System considerations determine how much information is needed from each vehicle and how often it should be sent. Prior work in automatic vehicle monitoring has usually emphasized the fixed-rate poling method of interrogating vehicles
to determine locations. If the polling method allows any or all vehicles to travel at maximum speed and still be located to the ultimate precision, the information flow is maximized from each vehicle. If an average speed is assumed for the fleet of vehicles, then high-speed vehicles will not be located to the precision available, and parked or slowly moving vehtcles will be transmitting much redundant data. Volunteer methods wherein the vehicle initiates a data transmission whenever a significant change in location has occurred require means to avoid contention and must also send additional data to 1 dentify which vehicle is transmitting. An adaptive polling technique whereby high-speed vehicles are interrogated at much shorter intervals and where average and slowly moving or parked vehicles are infrequently sampled is quite easily mechanized. The simplest polling technique requires that the central control transmit incrementing pulses (tones, or tone bursts) to all vehicles which count and accumulate these incremental signals. When the number of signals receaved matches the number assigned to the vehicle, a data transmission is initiated from the vehicle. The inclusion of a respond or do-notrespond pulse, tone, or burst with the incrementing signal will tell the vehicle whether data is required or not. Conversely, a vehicle which had been immobile could request inclusion in the next polling sequence by responding with an appropriate signal regardless of the command not to send data.

The amount that the AM carriers are off frequency together with the sampling intervals of the vehicles determines the number of bits required to be sent to the central command for location purposes. The length of each of the up-down counters is therefore determined by this number of bits. As stated before, two low-end of the band AM stations could cause an 80 Hz beat frequency in the synthesized 1 MHz signals which would cause a total count of about 288,000 per hour to be accumulated. A vehicle cruising at $30 \mathrm{~km} / \mathrm{hr}$ along the baseline of a station pair would accumulate a count of 200 per hour due in a stationary pattern. A recent Department of Transportation requirement for vehicle monitoring required that $25 \%$ of the vehicle fleet be located each 15 sec and the remainder located each minute. The total counts for each station pair under these requirements would be 1200 for 15 sec and about 5000 for the minute interval. To accommodate this requirement, the length of the up-down counters would have to be 13 bits each. Some 40 to 50 bits per interrogation would have to be transmitted from each vehicle if a preamble, parity checks, or error detection mformation was added to the basic 39 bits of location data. Assuming the higher number over a vorce channel from the vehicle which could conservatively accommodate $1200 \mathrm{bit} / \mathrm{sec}$, then 24 vehicles could be interrogated and located each second. Again using the DOT requirement, 820 vehicles could be located each minute, with 205 of the vehicles being located each 15 seconds, or four trmes each minute for a total of 1435 locations each minute ( 1440 maximum). It should be realized that these are theoretical maximum numbers and neglect the practical realities of turn-on stabilization time of mobile transmitters and also assumes another channel for interrogation purposes.

The amount of data required from each vehicle could be reduced by about two-thirds if the AM
stations being utilized for location maintaned phase coherency．A stationary lacation pattern would be generated，and the up－down counter lengths could be reduced substantially as only counts due to vehicle motion would be accumulated．Only a rela－ tively small amount of equipment would be neces－ sary at each AM station to maintain the carriers coherent to one another．This could be done by exther a common synchronizing signal or with each station referencing the carrier frequency to the other two carriers by counting and phase－locked loop techniques．In either case，the control range of the added equipment must not allow the carrier to be pulled outside of the 20 cycle FCC tolerance limit．

Some operational difficulties that might occur with this type of vehicle location system could be caused by momentary outages of one of the AM car－ riers，or transmitter switchover when power is increased or reduced．In some smaller metro－ politan areas it may be difficult to find three＂24－ hr＂broadcast stations with appropriate geometry， and different configurations may have to be used for day and night operation．

## G．Computer Simulation Programs

Two computer programs，a location simulator called LOCATE（Table 4－1），and a vehicle count

Table 4－1．Vehicle Location Simulator Program，LOCATE

```
        0.ocamectlop
\ LOCAEE
[1] XSN+1+XS,XS[1]
    N
    x+71[1]
    y+z1{2]
    RF}\mp@subsup{R}{R,+1}{X+2
    D+(((x-x5)*2)*(y-Y5)*2)*0 5
    D+DD[1]
    RE A[L]+((X-XS[L])=D[L ) -((X-XS[1])*D[1]
    ] REA[L]+((X-XS[L])&D[L))-((X-XS[1])*D[1])
    B[L}+((Y-YF[L])+D[L])-({Z-Y~[1])+U[1])
    CP[[L]+(D[L)]-D[1])-Q[L]+חC[r]
    ->RE\times1 (3\geqI-L+1)
    DFN+((4/A* ) x(+/J*2) )-(+/(A\times9))*2
```



```
    \DeltaY+(((+/A*2)\times(+/P*CV))-((+/1\times\mathcal{D})\times(+/A\timesCY)}))*DE
    z+x-\Deltax
20) }->PP\times1(({(\DeltaX)>10)v((|\Deltay)>10)
21] OTD*X,Y
22, IEL: X AIDD Y ARE , OLD
231 ' }\DeltaxAMD \DeltaY AR⿱一𫝀口' ( (\dot{x}-\chi),(y-y
```

generator called PIG（Table 4－2）were written to test the location method．A SETAUP program （Table 4－3）was also written which stores the loca－ tions of the AM stations in the arbitrary coordinate system and determines the lengths of the baselines connecting the stations．

In order to make the simulation more realistic， three AM stations in the Los Angeles，CA，metro－ politan area were chosen： $\operatorname{KFI}(640 \mathrm{kHz})$ located in the Buena Park－La Mirada area southwest of the Los Angeles Civic Center；KNX（ 1070 kHz ）in Torrance which is south and slightly west of the Cavic Center；and KMPC（ 710 kHz ）with transmitter in North Hollywood which is northwest of the Civic Center．The baseline distances are：KFI－KNX 31 km ，KNX－KMPC 35 km ；and KMPC－KFI 51 km ．

Table 4－2．Vehicle Hyperbolic Lane Count Generator Program，PIG

```
    vPIGTUJ%
    \nablaOID PIG Z2
(1) }XS-Z1+YC+DC-DD+CZR+CRT+N+Q+3P
[3] 
    x*+x1,x2,x]
    \mp@subsup{y}{5}{\prime}+\mp@subsup{y}{1}{\prime},\mp@subsup{y}{2}{\prime},\mp@subsup{Y}{3}{}
    DC-(((X-XF)*2)+((Y-Y&)=2))=0 5
    HO+(DC[2]-DC[1]).(DC[3]-DC[21),(DC[1]-DC[31)
    10-1104300
lal
[10] CTR+L(YO+FAI +0 5), CRR
[12] 
13] }\quady+\overline{Y}+22[2
14] }DD+(([x-XE)*2)+((Y-Y¢)*2))=0 
15] #H/(DD[2]-DD[1]).(DD[3]-DD[2]) (DD[1]-DD[3])
16] 7M+##1%*300
[17] CRN-L(M+LRHf+0 5),
[18] 'INE| COU iTEA IS ' CRT
193 M+CAT-CTR
[21] }\textrm{Q
```

Table 4－3．AM Broadcast Station Locations and Baseline Lengths Program，SETAUP

An arbitrary origin for the coordinate system was located some 8 km （ 5 mlles ）in the Pacific west of the Palos Verdes peninsula such that most of the area of interest for location purposes would be in the first quadrant of the $\mathrm{X}-\mathrm{Y}$ system．The ori－ gin is at $118^{\circ} 30^{\prime} \mathrm{W}$ and $33^{\circ} 45^{\prime} \mathrm{N}$ ．

The location（LOCATE）program and the vehicle count generator（PIG）program were written in APL computer language．The vehicle count gen－ erator requires two mput variables．These are the initial and terminal values in meters of the X－Y coordinates representing each change of posi－ tion of the vehicle．The hyperbolic coordinates of each location are calculated and the integral differ－ ence determined．The difference represents the counts that would be accumulated by a vehicle in traveling from the initial to the terminal location of each leg of travel．The count difference and the mitial location are the inputs to the LOCATE rou－ tine which determines the new location．The new location is determined by a reaterative technique whereby the deltas of $X$ and $Y$ which would satisfy
the change in counts of the hyperbolic coordinates are calculated and added to the initial location.

## H. Conclusions

A vehicle location method for use in metropolitan areas is avalable, which uses the carrier signal information from three currently operating AM broadcasting stations located near the urban perimeters. Two advantages of the method are that (i)
dedicated transmitters for location purposes are not required and that (2) the phase-lock-loop counting recervers installed in the vehicles are inexpensive. The mathematical technique for vehicle location is relatively simple and requires only that the initial location be known. While the technique is not explicit, location can be determined with adequate accuracy to the precision implied by the geometric configurations of the AM stations used and the frequency of the synthesized signal used for phase comparison.

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With the exception of the cut-to-fit development method, the evaluation of the buried loop* AVM system requares as a basis some mathematically analytic relations. Since such relations do not seem readily avalable in the open literature, an analytic approach was developed to determine the effects of loop spacings, dimensions, and height above roadway on RE signal detection and on rdentufication of the vehicle's location.

## A. Relationships of Three-Loop Vehicle Location System

The approach 1 s to find the mutual inductance of the vehicle's transmitter and receiver loops through the intermediary of the passive buried loop. A typical three-loop configuration is shown in Fig. 4-6. The assumptions are-

1. The XMTR and RCVR are sufficiently remote from each other so that direct mutual inductance is of secondary importance.
2. The buried loop is tuned with a capacitor to the vehicle transmitter frequency, and the buried loop resistance is durectly proportional to the number of turns.
3. The loops are in an isotropic medium.


$$
\begin{array}{ll}
I(T) & =X M T R \text { CURRENT } \\
K_{1}=X M T R / B L \text { COUPLING } \\
K_{2}=\text { RCVR/BL COUPLING } \\
N_{R}=\text { RCVR TURNS } \\
N_{T}=\text { XMTR TURNS } \\
N_{B L}=\text { BURIED LOOP TURNS } \\
R_{B L}=\text { BL RESISTANCE }
\end{array}
$$

Fig. 4-6. Configuration of Vehicle's Transmitting and Receiving Loops Relative to Buried Loop

1. Analytic Relations of Loop Mutual Inductances
(1) The magnetic flux lines $\Phi$ coupling the buried loop (BL) due to the XMTR current $I(T)$ at point $P$ is

$$
\Phi_{\mathrm{BL}}=\mathrm{K}_{1} \cdot \mathrm{~N}_{\mathrm{T}} \cdot \mathrm{I}(\mathrm{~T})
$$

where

$$
I(T)=I_{P} \sin (w t), K_{1}=X M T R / B L
$$

coupling, and $\mathrm{N}_{\mathbf{T}}=$ XMTR turns.
(2) The voltage E coupled to the buried loop with width $W$ is

$$
\begin{aligned}
& \mathrm{E}_{\mathrm{BL}}(\mathrm{~T})=\mathrm{N}_{\mathrm{BL}} \mathrm{~d} \Phi_{\mathrm{BL}} / \mathrm{dt}= \\
& \mathrm{W} \cdot \mathrm{~K}_{\mathrm{I}} \cdot \mathrm{~N}_{\mathrm{T}} \cdot \mathrm{~N}_{\mathrm{BL}} \cdot I_{\mathrm{P}} \cdot \cos (\mathrm{wt})
\end{aligned}
$$

(3) The current in the buried loop (which 15 at resonance), with resistance $R$, is

$$
\begin{aligned}
& I_{B L}(T)=E_{B L}(T) / R_{B L}= \\
& \quad\left[K_{1} \cdot N_{T} \cdot N_{B L} \cdot W \cdot I_{P} \cdot \cos (w t)\right] / R_{B L}
\end{aligned}
$$

(4) The flux lines coupling $K_{2}$ the RCVR due to the buried loop is

$$
\Phi_{R C V R}(T)=K_{2} \cdot N_{B L} \cdot I_{B L}(T)
$$

substituting

$$
\begin{aligned}
& \Phi_{R C V R}(T)= \\
& {\left[-K_{1} \cdot K_{2} \cdot N_{T} \cdot\left(\mathrm{~N}_{B L}\right)^{2} \cdot \mathrm{~W} \cdot I_{P} \cdot \cos (\overline{\mathrm{w} t)}]\right] /} \\
& \mathrm{R}_{\mathrm{BL}}
\end{aligned}
$$

(5) The voltage at the RCVR due to the buried loop is

$$
\begin{aligned}
& E_{R C V R}=N_{R} d \Phi_{R C V R} / d t= \\
& {\left[-K_{1} \cdot K_{2} \cdot N_{X} \cdot N_{B L} \cdot N_{R} \cdot\left(W I_{P}\right)^{2} \cdot \sin (w t)\right] /} \\
& R_{L O O P}
\end{aligned}
$$

allowing now the resistance per turn (R/turn)

$$
\begin{gathered}
R_{l o o p}=(\mathrm{R} / \text { turn }) \cdot \mathrm{N}_{\mathrm{BL}} \\
\text { QED } \cdot \mathrm{E}_{\mathrm{RCVR}}=\left[-\mathrm{K}_{1} \cdot \mathrm{~K}_{2} \cdot N_{\mathrm{T}} \cdot \dot{N}_{\mathrm{BL}} \cdot \mathrm{~N}_{\mathrm{R}} \cdot\right. \\
\left.\left(\mathrm{W} \mathrm{I}_{\mathrm{P}}\right)^{2} \cdot \sin (\mathrm{wt})\right] /(\mathrm{R} / \text { turn })
\end{gathered}
$$

[^4]2. Comments. The reasoning involved in deriving the relationship permit the geometrical and electrical aspects of the solution to be separable and simply multiplicative. If $\mathrm{E}_{\mathrm{rcvr}}$ is to be of the form MdI/dt then:
$\mathrm{M}_{\text {equivalent }}^{\text {becomes }\left[\mathrm{K}_{1} \cdot \mathrm{~K}_{2} \cdot \mathrm{~N}_{\mathrm{C}} \cdot \mathrm{N}_{\mathrm{R}} \cdot \mathrm{N}_{\mathrm{BL}} \cdot(\mathrm{WIP})\right] /}$ ( $\mathrm{R} / \mathrm{turn}$ )
and
$$
I(t) \text { becomes } I P \cos (w t)
$$
B. Magnetic Field Generated by Rectangular Loop of Wire

1. Development of Flux Density Equations. It is desired to find the flux intensity $B$ at a point $P(x, y, z)$ generated by the rectangular loop of wire, with the X -axis direction across the lane width and the Y -axis in the direction of roadway travel.

## Given:

(1) A rectangular loop of wire of length $L$ and width $W$, with the lane width equal to the buried loops length.
(2) The loop is in a free-space plane (of $x, y, z$ rectangular coordinates) having equations $z=0$.
(3) The loop has a DC current of I.
(4) The coordinate space has its origin at $(0,0,0)$, which is the center of the loop wire.
(5) The lankage or mutual inductance of two parallel planar loops (not necessarily coplanar) lying in $x, y$-plane uses only the $z$-component of flux density.

Method:
(1) Decompose the loop into four linear segments
(2) Apply the Biot Savart law from each segment to the point of interest

$$
\left|B_{p}\right|=\left(\frac{\mu}{4 \pi}\right) \cdot\left(\frac{I}{a}\right) \cdot(\cos \gamma-\cos \alpha)
$$

(3) Decompose the flux density into its vector components, and sum the components.

The complete mathematical analysis is presented in Ref. 1.

## C. Computer Programs for Calculating Mutual Inductance

Two programs are used to generate the mutual inductance of rectangular wire loops. The programs LOOPS and CARCUP are written in the Stanford Artıficial Intelligence Language, "SAIL," which is an extended ALGOL 60.

1. "LOOPS" and "CARCUP" Programs. The "LOOPS" program is used to find (1) the XMTR/RCVR direct mutual coupling, (2) the self inductance of a loop, and (3) the direct coupling
between the Buried Loop and the XMTR or between the Buried Loop and the RCVR or between two Buried Loops. The "CARCUP" program is used to find the mutual coupling between the XMTR and the RCVR via the Buried Loop, the inner workings of the two programs are similar, the program "CARCUP" is, in effect, the program "LOOPS" run twice. Both of the programs have Input/Output in common.
a. LOOPS Program. This program (Table 4-4) asks the user. (1) if he wants more detailed information, (2) to specify 'how many steps," or data points, (3) where is the starting point of the pickup loop and what size is the loop (in terms of XMIN, XMAX, YMIN, YMAX) and how, high above the buried loop (in terms of $Z$ ), (4) to specify the aspect ratio of the buried loop, K.

The LOOPS program calculates and prints out the mutual inductance for the number of data points specified. Each successive data point represents the mutual inductance of the buried loop and pickup loop moving along the positive $Y$ direction (along the roadway lane) by $1 / 10$ of its length (i. e., (YMAX-YMIN)/10). The mutual inductance is in relative units. To find the answer in henrys, multiply the answer by half the lane width (in meters), by $10^{-7}$, by the number of turns of the buried loop, and by the number of turns of the pickup loop.
b. CARCUP Program. This program (Table 4-5) asks the user: (1) if he wants more detailed information, (2) to specify 'how many steps," or data point, (3) where is the starting point of the XMTR loop, and what is its slze and how high above the buried loop (in terms of XTMIN, XTMAX, YTMIN, YTMAX, ZT); also where is the starting point of the RCVR loop and

Table 4-4. LOOPS Program for Mutual Inductance of Buried/Pickup Loops, and Sample Run

|  |  |
| :---: | :---: |
| 00150 | IHTERHLFL INTEGEP EXIT ,FDPER.; |
| 00209 | INTEGEF I, J, 3 ,EFK, |
| 00300 | DEFINE RF=-'15\% $12-$; |
| 09400 |  |
| 00500 |  |
| 00556 | STRING ST, |
| 00000 |  |
| CRR RET) |  |
|  |  |
| 00800 | IF IHCHILE"YES" TREH CUTSTRく" |
| 00900 |  |
| 01000 | RELATIVE CEUPLINT RETVEEN TWI FLAT EUT WICM CDPLAIHAR FECTAMNULAP |
| 01100 |  |
| 01200 | fXES DE PEFPAHEE) $1 T$ tS 70 ee APPLIED IH flotomative vehicle |
| 01300 |  |
| 01400 | THE LFISE UIDTH I $\sim$ ThE 2 DIMENSION ThE LANF LEEHETH IS |
| 01500 |  |
| 01600 | ב DIMENSIDM TNE CENTEF DF THE EJPIED LCCF IS fit COURDINATES |
| 01700 | O,O,0 THE MIDTH GF THE EURIED LOUF IS THE LANE WIDTH |
| 01800 |  |
| 01900 | LERGTM) |
| 02000 |  |
| 02109 | PICRUP LOAP |
| 02200 | hll infut diliensions rre to ee hormaigized to hflf the late |
| 02500 | WIDTH. |
| 02400 | HON MRITY STEPS PEFERS TO MOVINS ThE P IEYlup LGOP ALING |
| 02530 | THE LAhE LENGTHCREhERALLY ALAMY FOGM hEOFE THE EURIED LEGP) BY |
| 02600 | 1/10 OF THE PICPUF LEISP LERIGTH GIHD THEN CALCULETEITE ITS |
| 03700 | HEPMALIEED 2 DIFECTIG. CEUFLING FPOH THE BUFIED LOCF |
| 03800 |  |
| 02900 | RHD OF SICCESSIrE STEFFING: |
| 03000 | TO FIND THE GCTURL FLIM IN YOLT SECDHDS, MULTIfLY' the deta |
| 03100 | BY THE FGLLEWING FPCTCP: |
| 03200 | (I)* (LANE WIDTH/2) - (10t (-7) ) |
| 03305 | WHEPE I IS THE BURIED LGEP CUFRENT III PIIPS |
| 03400 | WRERE THE LANE HIDTH IS IN :ETERS-8RF); |
| 03500 | OUTSTRく"HDN MANY STEPS ")i |
| 03000 |  |
| 03550 | PEEIN |
| 03700 | PERL ARRAY YC1803, |
| 03900 |  |
| 03900 |  |
| 04000 |  |
| 04100 |  |
| 04200 |  |

Table 4－4．（Continued）

| 04300 | Y－YMIN YA + （MAS－YMIH）／103 |
| :---: | :---: |
| 04400 |  |
| 04\％ 06 | T＋0，$=1, \mathrm{~B}+0$. |
| 04000 |  |
| 04706 | $\mathrm{E}+\mathrm{I}+$ 2， $\mathrm{l}+1 \mathrm{i}+1$ |
| 0.4300 |  |
| 04906 | EXIT＋a，FORER＋G |
| 05959 | BEGIT |
| 05000 | PRDEEPAFE FIZ， |
| 05100 | BEGIN |
| 05200 | $\mathrm{R}+(X+1), 5+(Y-1)$, |
| 05300 | $C+(Y+k), D+(Y-K)$ ． |
| 05400 | $\mathrm{AR}+(\alpha+1)+2, \mathrm{CC}+(Y+Y)+E$ ； |
| 05500 |  |
| 05 c 09 |  |
| 05700 |  |
| 05300 |  |
| 05900 | $\mathrm{R}+-(\mathrm{Br}(\mathrm{E}+\mathrm{BB})$ ）$<(-\mathrm{D} / \mathrm{H}+\mathrm{C} / \mathrm{H})$ ； |
| 06000 | $\mathrm{L}+(\mathrm{C} /(\mathrm{E}+\mathrm{CC}))+(-\mathrm{E} / 31+8 / \mathrm{G})$ |
| 05100 | M＋－（D）$(E+\mathrm{DD})$ ）$+(-\mathrm{E} / \mathrm{H}+\mathrm{fi} / \mathrm{F})$ ； |
| Wsedo |  |
| 95300 | EMD， |
| $05+00$ |  |
| 05500 | PRDEEDLFE FLURCUP， |
| 00000 | BEGIM |
| 05050 | SETFDRMAT（13，3）， |
| 06700 |  |
| 05800 | EEGIN |
| 06900 |  |
| 07000 | BEGIM |
| 07100 | EIZ；T＋T＋EE，X－Y＋XA |
| 07200 | EMP． |
| 07300 | V［S $3+\mathrm{T}, \mathrm{X} \leqslant$＜mIN， $\mathrm{Y}-\mathrm{Y}+\mathrm{Y} \mathrm{F}, \mathrm{S}+\mathrm{S}+1, \mathrm{~T}+0$ |
| 07400 | END， |
| 07500 | UHILE $\$ LEO（S－i0）DI  \hline ap600 & BEGIN  \hline 0770a & WHILE（ $5+10$ ）${ }^{\text {l }}$ D D |
| 07800 | BEGIH |
| 07900 | 0－ $0+4 \mathrm{C} 1 \mathrm{l}, 1+1+1$ |
| 03006 | END． |
| 03100 | UUTSTR（CVEくは）， |
| \％s200 |  |
| 108300 | EmD， |
| 09400 | End． |
| 03500 | FLUSCUP． |
| 09550 | EMD，END 3 |
| 05000 | EMD＂LOCPS ${ }^{\text {a }}$ |

PUH LOGPS＿RY
D Y Yov whit notes＜tyfe in eithef yes di ho gallatien i，tar pet y yes
The puppace df this ffirffil is to calcilfite the ffee grace RELATIVE CDUFLING EETLEEN TWQ FLHT SUT HCH COFLGHME PECTRHGULAP LDLPS UF LIREKTKE SIDES DF HHITH ARE FAFNLLEL TD THE CGERDIRATE


 THE DIMENSIDN．THE EEHTEP OF THE BUPIED EDOP IS HT CBERPINGTES K IS THE FSFECT FHTID DF THE EUFIES LODP 《WIDTH DIYIDED EY LENGTH，
 PICr LFP LDEP
fll infut dimensions moe ta pe ncpmalized to half the larie MIDTH．
HOE LAHE SENTEPS PEFEPS TO LIGVINA TRE FICKIJP LCLP RLOMG
 ROFMGLIEEL 2 DIRESTICR COUPLINE SKOM THE EHFIED LOCP THE FFINTOUT IS THE PALCULATED FLUY IN PELATIYE FLUW UNITS AHI OF CUCCESSIVE STEPFINGS
TQ FINE THE HETHML FLII IN VELT SECGMDS，MULTIPLS THE DHTA \＄）THE FELLDIAMF FFCTOD
WHERE 1 I THE EUFIED LOCF FIIFPEMT IN RRPS
LIHERE THE LANE LJIDTH IS IN METEKS
HOW MHTY STEPS 100
YMIII $=-1$
《MA\＝1000
$\operatorname{yMIN}=-0001$ 00
$\operatorname{manx}=1$
$\ddot{0}=0$
$K=1$

| －34352 | －100さ\％ | 10839 | 102．9 | －10299 |
| :---: | :---: | :---: | :---: | :---: |
| －105\％9 | $102{ }^{\text {a }}$ | 10279 | 10299 | $103{ }^{\circ} 9$ |
| －10259 | －530\％1 | － 30121 | －19221 | －13501 |
| －． $100 \% 1$ | －． 770 | －－007 | － 489 | －． 401 |
| － 334 | － 381 | －こここ | － 205 | － 178 |
| － 155 | － 130 | －． 120 | －． 107 | －9502－1 |
| －85ts－1 | － 7659.1 | －6919－1 | － 0 26－9－1 | －5uap－1 |
| －5193－1 | － 4750 －1 | －4352－1 | －40\％${ }^{-1}$ | －3n＊）－1 |
| －． －$_{\text {－}}$ | －315\％－1 | －2930－1 | － 7 72か－1 | －2532－1 |
| － 2 人09－1 | －2c0\％－1 | －2069－1 | －1903－1 | －18101－1 |
| －．1703－1 | －โ6uy－1 | －1517－1 | －142゙ー－ | －1342－1 |
| －12－0－1 | －1200－1 | －1147－1 | －1052－1 | － $1027-1$ |
| －9709－2 | －．9－20－を | －5779－2 | －835\％－2 | － $7967-2$ |
| － 7 －${ }^{\text {ata }}$ | －． 72.47 － | －5920－3 | －－5617－2 | －．6327－2 |
| － $0051-2$ |  | －555\％－2 | －532จ－3 | －+ 5117－2 |
| －4002－2 | －4710－2 | －－4532－2 | － 4352 s － | －$-4187-2$ |
| －403， | －З3ss | － 374802 | － $3002-z$ | － $3479-2$ |
| －．3352－3 | －3ミ3゙－2 | －${ }^{-3120-2}$ | －-3017 － | －${ }^{-3919-2}$ |
| －2382－3 | －ごさワ－ | －3n39－を |  | －24\％ |

Table 4－5．CARCUP Program for Mutual Inductance of XMTR／RCVR Loops， and Sample Run


Table 4－5．（Continued）
．RUN CARCUP．SAY

TO FIND THE AFTUFL GUTPUT VOLTS，MULTIFL＇THE DATA BY THE gOLLDHIHG
 WHERE

NBL $=$ KIMEER OF TURNS ON THE BURIED LIGP
NR $\equiv$ NUMBER IF TURAS DN
LANE WIDTH IS IN METERS
Wane $=24$ PI 4 F
$\mathrm{F}=$ 2\＆PANSMITJER FREOUENCY（HERTZ）
IP＝THE PERK TRANSMITTER CUPFENT
SIM（NT）＝YOU KNGU YHFT
$\mathrm{R}=$ THE PER TURN RESISTANCE aF TRE EUPIED LOCP

HDL Mank steps 30
ATMING 45
XTMAXA 55
YTMIN $=-05$
YTMIN $=-05$
YTMAX $=05$
$Y T M A K=0$
$Z T=.1$
XRMIN $=-.55$
XRMAX $=-.45$
YRMIN $=-05$
YRMAX $=05$
ZR＝． 1
$K=4$

| 119アー1 | 119 －1 | 1203－1 | ．1209－1 | 1208－1 |
| :---: | :---: | :---: | :---: | :---: |
| 121\％－1 | 12こう－1 | 123ワ－1 | ．1259－1 | 120ッ－1 |
| 128す－1 | $130 \hat{\text {－}}$ | 132จ－1 | ．1348－1 | 1379－1 |
| ．1402－1 | 143จ－1 | 1472－1 | －1508－1 | －1542－1 |
| ．1592－1 | －1630－1 | 163）－1 | －1728－1 | －1770－1 |
| 1812－1 | 1859－1 | 1239－1 | ．1912－1 | ．1912－1 |
| ．1892－1 | OF SAIL |  |  |  |

what is its size and how high above the buried loop （in terms of XRMIN，XRMAX，YRMIN，YRMAX， ZR），（4）to specify the aspect ratio of the buried loop，K．

The CARCUP program calculates and prants out the mutual inductance for the number of data points specified．Each successive data point represents the mutual inductance of the XMTR／RCVR through the buried loop by moving along the positive Y－ dixection（along the roadway lane）by $1 / 10$ of the XMTR Iength．The results are in units of relative mutual inductance and to get real answers，answer ＂yes＂when the program asks if you want more de－ tailed information．

2．Method of computing．The inputs to the program（XMAX，YMIN，etc．）describe the area swept out by the motion of the pickup loop（s）．The program calculates the mutual inductance between the entire buried loop and portions of the swept－out area using elements of area $1 / 10$ the pickup loop width by $1 / 10$ the pickup loop length．

$$
\begin{aligned}
& \Delta X=(X M A X-X M I N) / 10 \\
& \Delta Y=(Y M A X-X M I N) / 10
\end{aligned}
$$

The swept－out area is divided into portions having dimensions $\triangle Y$ by（XMAX－XMIN）．There are（ $10+$＂how many steps＂）portions．The mutual inductances are calculated and stored for those portions．

Summing the values of 10 successive portions yields the mutual inductance of the buried loop to one particular position of the pickup loop．

The CARCUP program sums the corresponding 10 successive portions of both XMTR and RCVR and multiplies them together to get the overall mutual inductances．There are two main subrou－ tine procedures used to calculate the mutual induc－ tances，BIZ and FLUXCUP．With respect to the

BIZ subroutine，the flux density is calculated for that corner of the area XA by YA which is closest to the point（XMIN，YMIN）．With respect to the FLUXCUP subroutine，FLUXCUP in the LOOPS program differs from FLUXCUP in the CARCUP program，the difference being in form only for the purpose of minimizing data handling．

## D．Optimum Relative Configuration of Three－ Loop AVM System

1．Buried loop interaction with adjacent coplanar loops．The results seem to favor loops having aspect ratios of $\geq 1$ ．However，the practical aspect of packing the buried loops as densely as possible is a primary consideration．At any rate， If $K$ is greater than 0.025 ，a center－to－center spacing of the buried loops of greater than $4 \times \mathrm{K}$ （i．e．， 2 times the loop width along the lane）results in a coupling of less than $5 \%$ of the same loops superimposed．

2．XMTR and RCVR direct coupling．If it is presumed that the XMTR and RCVR loops＂ought to be the same，＂then the results seem to favor loops having aspect ratios $\geq 1$ ．That is，the loops should be rectangular and have their＂small ends＂pointed toward one another．The XMTR and RCVR on the vehicle are small compared to the buried loop． The choice of their aspect ratios has a limit to avoid extending beyond the buried loop．

At any height，sensors having more turns on smaller loops are as effective as ones with large loops having fewer turns．At any helght the coupling varies with later position，being highest near $0.8 \ell$ from center to end of the buried loop．The variation between these limits is about $10 \%$ ．

If a sensor loop is placed lowex than the optl－ mum height，it results in overcoupling and rela－ tively high noise signal，thus also reducing buried loop packing density．This is most pronounced for buried loop aspect ratios much greater than pickup loop size．XMTR and RCVR coils of duffering shapes will function and may permit three－loop systems whereby the smallest moving coil may be made the optimal for signal to＂nois e＂ ratio．

3．Expected real－life signal levels．The following configurations and conditions are as－ sumed：（1）Roadway with lane width $2 \ell=3$ meters， （2）buried loops with aspect ratio $\mathrm{K}=0.1$ and separated by $4 \times \mathrm{kx} \mathrm{\ell}$ ，（3）pickup loops（XMTR and RCVR）having sides $P=0.1 \ell$ ，height $Z=0.1 \ell$ ， and separated by $\ell$ ．（4）All loops have 10 turns each of \＃27 wire and resistivity of $1.36 \mathrm{ohm} /$ meter． （5）The transmitter is producing 100 kHz at 1 amp peak．（6）Self－inductance of buried loop 495 microhenrys．（7）Mutual inductance of two buried loops 20.25 microhenrys．（8）XMTR／RCVR self－ inductance 7.87 microhenrys each．（9）Direct mutual inductance of XMTR and RCVR 0.0045 microhenry．（10）Three－loop system maximum mutual inductance 1.24 microhenrys．（11）Voltage signals produced by XMTR／RCVR direct coupling 2.8 mV cos wt ．（12）Voltage signals produced by three－loop system－0．78 mV sin wt．
4. Comments. The direct coupling of the ransmitter and recelver produces a voltage at the recenver of contant peak amplitude, having the transmitter frequency and shifted in phase by
+90 degrees. The three-loop system response envelope is a function of the vehicle speed. The output frequency is shifted 180 degrees with respect to the input current frequency.

## REFERENCE

1. Zottarelli, L. J., "Burried Loops," JPL Interoffice Memo addressed to G. R. Hansen, 1974.

[^0]:    ＊Costs as of 1974.

[^1]:    * Costs as of 1974.

[^2]:    *Costs as of 1974.

[^3]:    *U.S. Patent 3,889, 264.

[^4]:    *U.S. Patent 3,772, 691, "Automatic Vehicle Location System,"

