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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

This document on Automatic Vehicle Monitoring Systems presents the results of work supported by the National Science Foundation. It was sponsored under an interagency agreement with the National Aeronautics and Space Administration through Contract NAS 7-100. Points of view and opinions stated in this document are those of the authors and do not necessarily represent the official position of the sponsoring agency.

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 various 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 administrative control and public relations information. This complete report and the Executive Summary (Vol. 1) were prepared by the Jet Propulsion Laboratory of the California 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 will best suit their individual performance requirements and also the possible reduction in the number of vehicles needed which could substantially reduce operating expenses.

G. R. Hansen

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Lieut Robert Zippel	Anaheim
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Lieut James Lance	Long Beach
Chief Raymond McLean	Montclair
Lieut Allen Stoen	Monterey Park
Ofc. Luke Villareal	Pasadena
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Chief William Mooney	Long Beach
Chief Raymond McLean	Montclair
Chief Raymond Warner (dec)	Monterey Park
Chief Robert McGowan	Pasadena
Chief Raymond Hoobler (ret)	San Diego

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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 obtainable 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 applications and coverage data are tabulated for seven cities whose police departments actively cooperated in the JPL study. Volume 1 of this Report is the Executive Summary. Volume 2 contains the results of systems analyses.

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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 Propulsion Laboratory (JPL) for the National Science Foundation (NSF). As originally conceived by NSF and JPL, the AVM Systems study program would include the following three phases:

Phase 0	Problem Definition and Derivation of AVM System Selection Techniques (in this Report)
Phase I	Critical Research and Verification of the Efficacy of AVM System Selection Techniques Through Computerized System Simulation.
Phase II	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 characteristics, (2) adaptation of computerized 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 monitoring (AVM) was compiled from the existing literature, including: (1) Various 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 obtained from the literature was supplemented by data obtained directly from police department representatives of seven Southern California cities that participated 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. Preliminary analyses of the accuracies achievable with various AVM systems were also performed. Various AVM system configuration options were developed, and promising options were examined 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 (i.e., piloting, deadreckoning, triangulation, trilateration, and proximity) do not necessarily 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 monitoring classifications were based on system element types and functions as follows:

Class 0	Manual Monitoring. No AVM
Class I	AVM. No modification to the urban environment. (existing 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 km^2 (40 mi^2) 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. <u>Vehicle polling intervals determine AVM system accuracies.</u> 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. <u>Critical research required for verification of selection technique.</u> 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 verify 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 California 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 classified in the literature 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-vehicle equipment, 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 synchronized RF transmitter sites (Class III).
(11) 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 consideration, AVM systems 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 supplying 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 RF 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 communication 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 communication 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 voice 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 receives 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 vehicle'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 vehicle may be by radio, pulsed light, infrared, sonic, 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 determine 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 receive 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 its 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 vehicle 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 Monitoring; No AVM. This baseline (piloting) class is included in the listing of vehicle location techniques purely for comparative purposes. In Class 0, the location monitoring methods (Figure 1) 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.

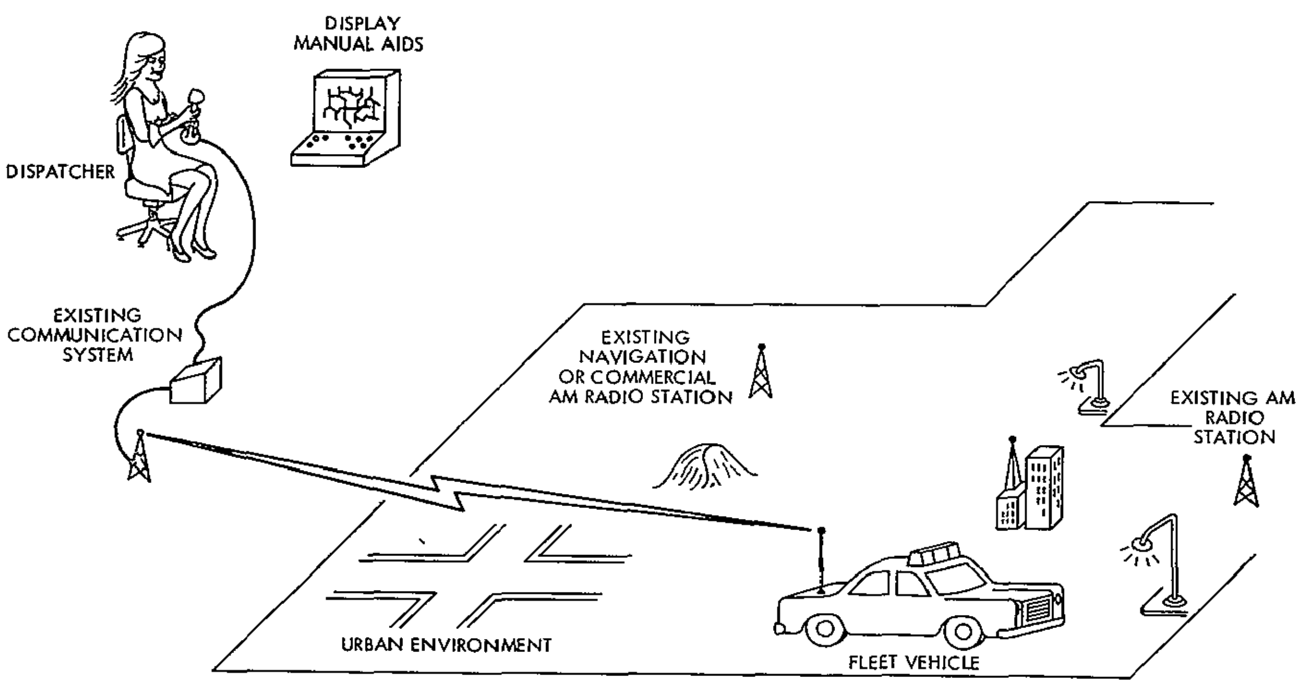


Figure 1. Class 0 Manual Monitoring, No AVM

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 vehicle 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 techniques 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. <u>Class II AVM with autonomous signposts throughout urban areas.</u> 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.

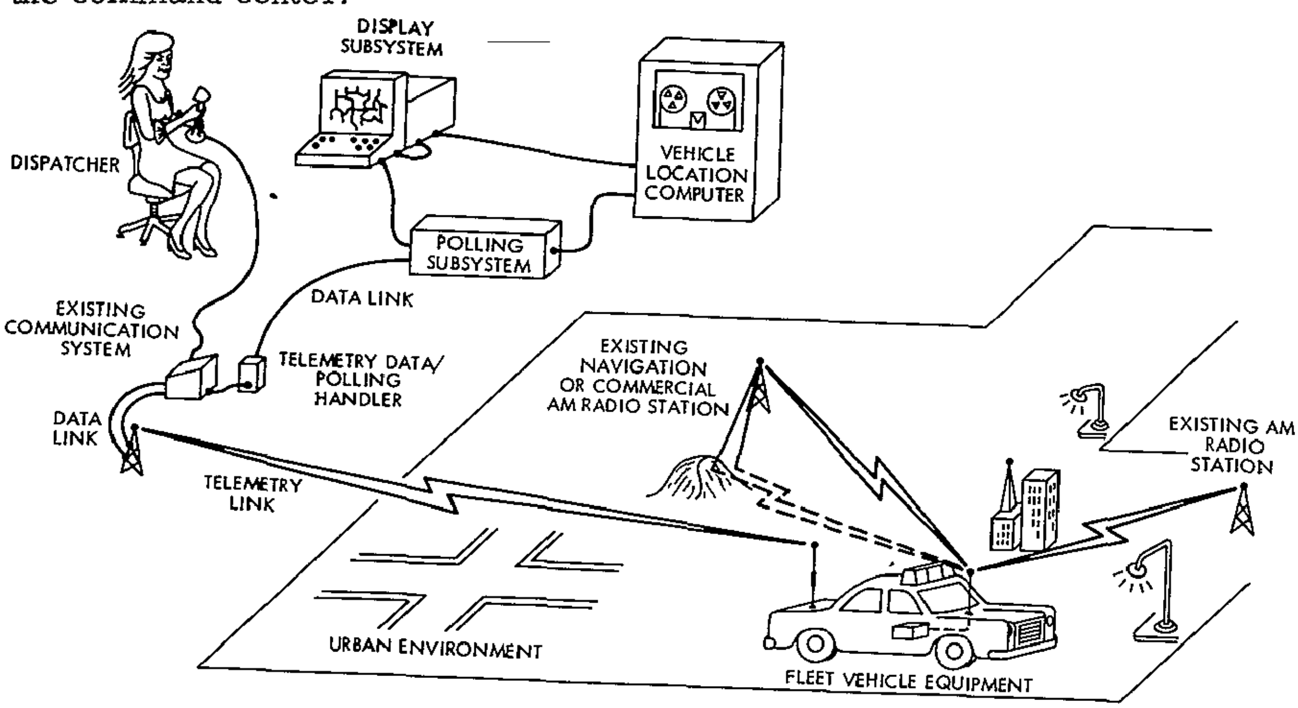


Figure 2. Class I AVM; No Modifications to Urban Physical Environment

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 achieved 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, calibrate, 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. This 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 receives over a relatively large urban area with a radius of 5 to 11 km (3 to 7 miles).

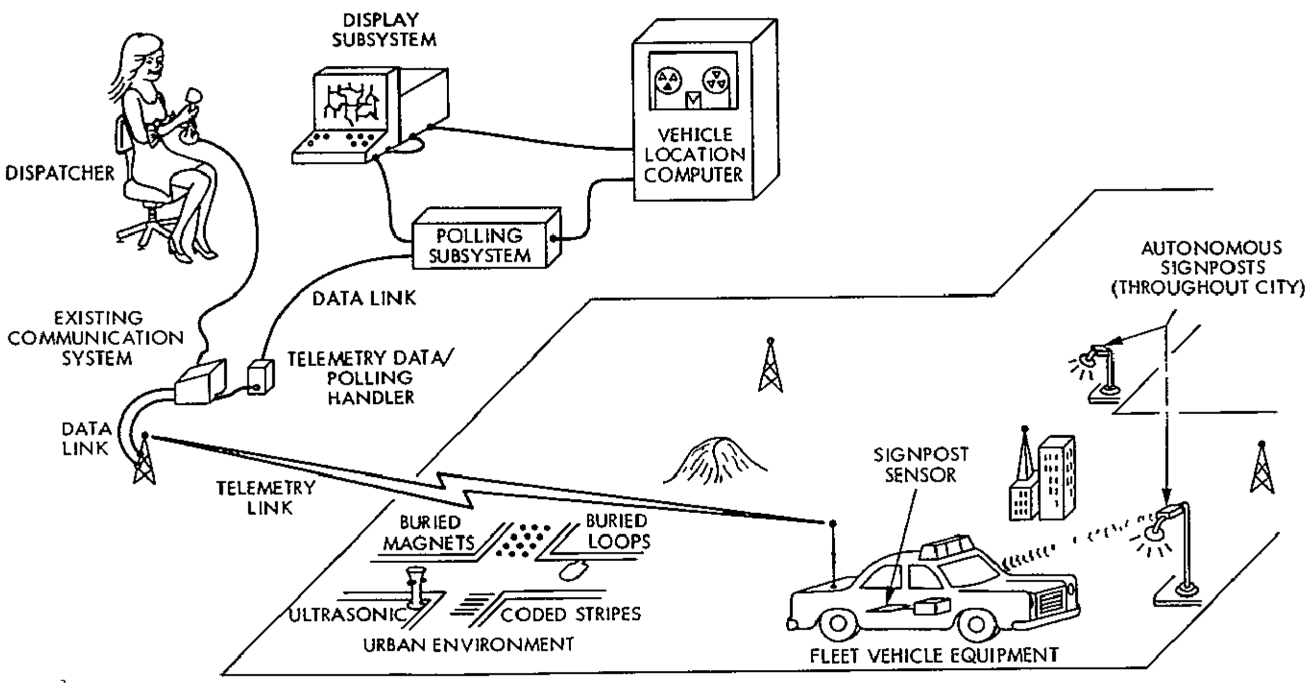


Figure 3. Class II AVM, Autonomous Signposts Throughout Urban Area

Data links in the environment are required to maintain synchronization for triangulation or trilateration purposes. Since the number of fixed sites is relatively small, these data synchronization links could be microwave rather than landline. Figure 4 shows a typical 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 wayside 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 link 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.

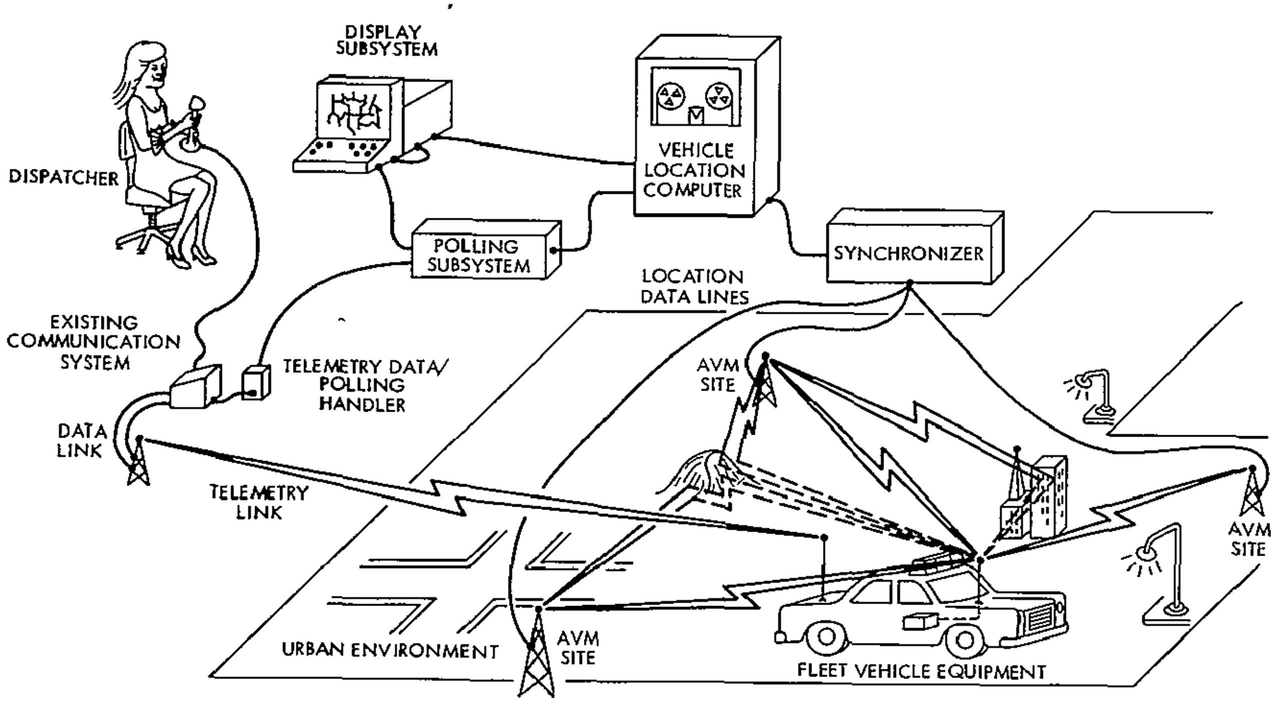


Figure 4. Class III AVM; Sparsely Distributed Special RF Sites

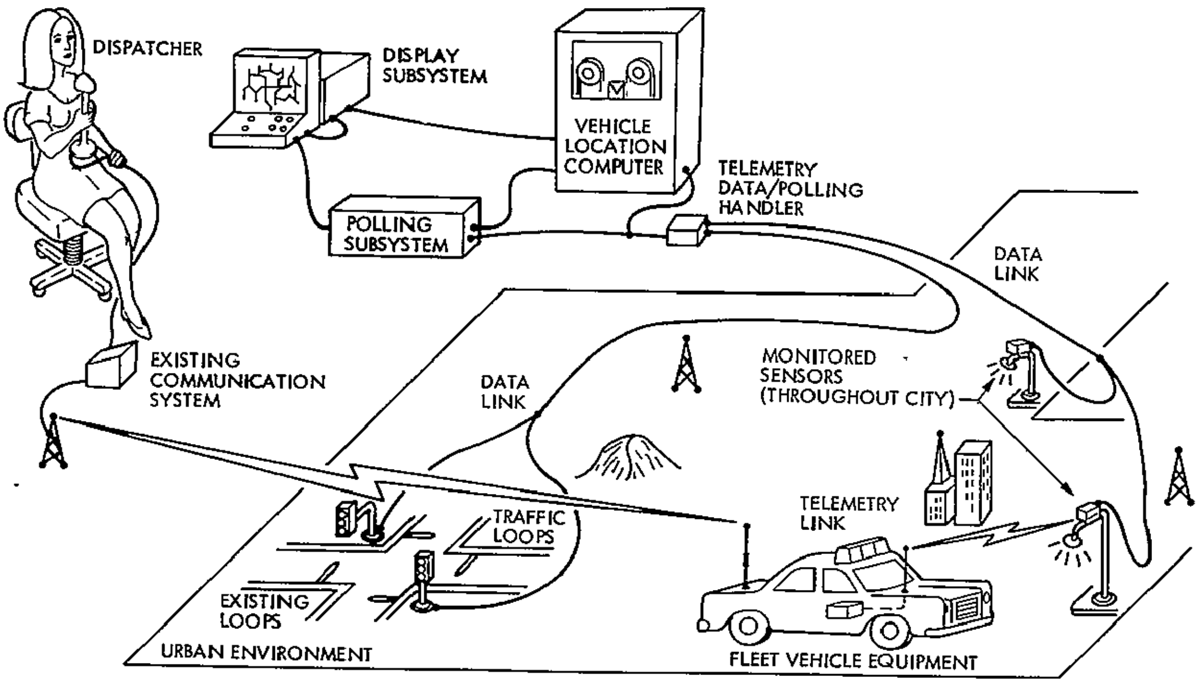


Figure 5. Class IV AVM, Monitored Signposts Throughout Urban Area

IV. VEHICLE LOCATION TECHNOLOGIES AND COSTS

A. PROVED AVM TECHNIQUES

This section contains a narrative description and a compilation 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 transmitting/receiving fixed RF sites; and Class IV AVM, densely distributed monitored signposts. In Table 1, 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.

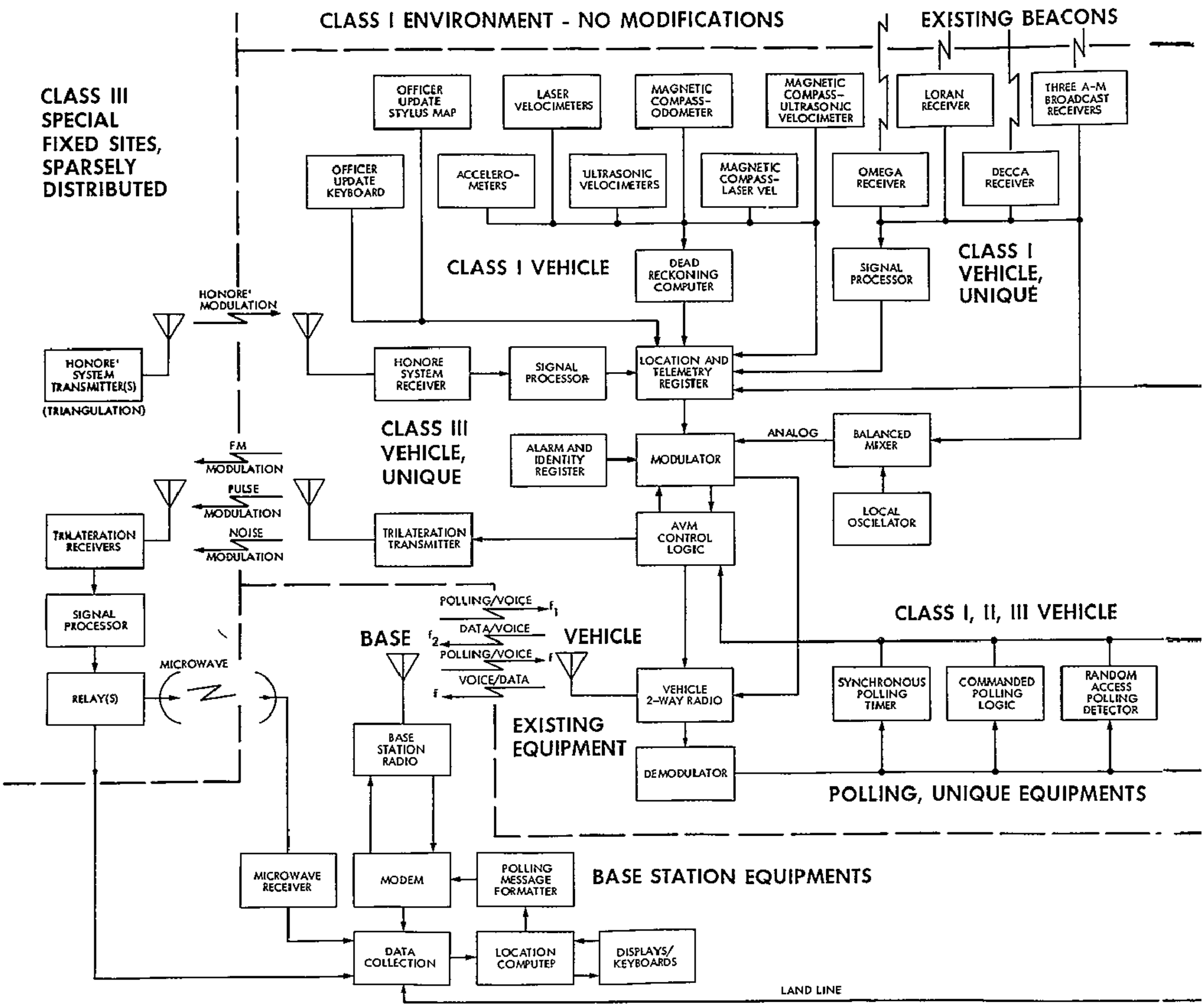
1. Functional diagram correlating various AVM techniques. In order to make equipment and cost comparisons, a functional block diagram combining the elements that make up all of the AVM techniques was generated. This block diagram (Figure 6) demonstrates the equipment and functional commonality among the various techniques. In most techniques, the functional elements can also be physically identical, such as the location/vehicle 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, $	
	Vehicle	Fixed Site
Class 0. Manual Monitoring No Augmentation of Vehicle Location Information		
Class I. No Modifications to Urban Environment (Existing RF Links)		
(1) Officer update systems	—	—
(a) Keyboard entry	120	0
(b) Stylus map	2535	0
(2) Dead reckoning systems	—	—
(a) Two accelerometers	500	0
(b) Two velocimeters	—	—
Laser, orthogonal	715	0
Laser/compass	805	0
Ultrasonic	485	0
(c) Odometer/compass	—	—
Magnetic compass	285	0
Gyro compass	—	0
(3) Navigation, existing beacons	—	—
(a) OMEGA systems	—	—
Differential	1580	0
Relay OMEGA	455	0
(b) LORAN (A, C, or D)	—	—
Differential	2680	0
Relay LORAN	505	0
(c) DECCA System	1010	0
(d) AM Broadcast stations	365	0

AVM Class and System	Element Costs, $	
	Vehicle	Fixed Site
Class II Autonomous Signposts Throughout Urban Area		
(1) Active signposts	—	—
(a) Radio beacons	—	—
Low frequency	145	165
Citizen band, VHF	145	145
X-band beacon	160	275
(b) Ultrasonic signposts	170	160
(c) Optical, infrared	170	155
(d) Buried antennas	135	120
(2) Passive signposts	—	—
(a) Buried Magnets	95	110
(b) Reflective patterns	—	—
Coded on signposts	580	85
Coded on roadway	135	125
(c) Buried resonant loops	135	95
Class III. Sparsely Distributed Special RF Sites		
(1) Trilateration systems	—	—
(a) Phase TOA	—	—
Narrow-band	100	5,000
Wide-band	2,965	11,000
(b) Pulse TOA	1,435	14,500
(c) Interferometer, noise	885	9,000
(2) Triangulation systems	—	—
(a) Rotating beams (HONORÉ)	—	—
(b) Direction finding	50	27,500
Class IV Monitored Signposts Throughout Urban Area		
(1) Radio receivers	—	—
(a) Wayside	135	260
(b) Buried antennas	145	265
(2) Ultrasonic receptors	185	280
(3) Optical, infrared detectors	185	270



CLASS I ENVIRONMENT - NO MODIFICATIONS
EXISTING BEACONS
CLASS III SPECIAL FIXED SITES, SPARSELY DISTRIBUTED
OFFICER UPDATE STYLUS MAP
LASER VELOCIMETERS
MAGNETIC COMPASS-ODOMETER
MAGNETIC COMPASS-ULTRASONIC VELOCIMETER
LORAN RECEIVER
THREE A-M BROADCAST RECEIVERS
OFFICER UPDATE KEYBOARD
ACCELERO-METERS
ULTRASONIC VELOCIMETERS
MAGNETIC COMPASS-LASER VEL
OMEGA RECEIVER
DECCA RECEIVER
CLASS I VEHICLE
DEAD RECKONING COMPUTER
SIGNAL PROCESSOR
CLASS I VEHICLE, UNIQUE
HONORE' MODULATION
HONORE' SYSTEM TRANSMITTER(S)
(TRIANGULATION)
HONORE SYSTEM RECEIVER
SIGNAL PROCESSOR
LOCATION AND TELEMETRY REGISTER
CLASS III VEHICLE, UNIQUE
FM MODULATION
PULSE MODULATION
NOISE MODULATION
ALARM AND IDENTITY REGISTER
MODULATOR
ANALOG
BALANCED MIXER
LOCAL OSCILLATOR
TRILATERATION RECEIVERS
TRILATERATION TRANSMITTER
AVM CONTROL LOGIC
SIGNAL PROCESSOR
POLLING/VOICE
DATA/VOICE
POLLING/VOICE
VOICE/DATA
BASE
VEHICLE
CLASS I, II, III VEHICLE
MICROWAVE
RELAY(S)
VEHICLE 2-WAY RADIO
SYNCHRONOUS POLLING TIMER
COMMANDED POLLING LOGIC
RANDOM ACCESS POLLING DETECTOR
BASE STATION RADIO
EXISTING EQUIPMENT
DEMODULATOR
POLLING, UNIQUE EQUIPMENTS
MICROWAVE RECEIVER
MODEM
POLLING MESSAGE FORMATTER
BASE STATION EQUIPMENTS
DATA COLLECTION
LOCATION COMPUTER
DISPLAYS/ KEYBOARDS
LAND LINE

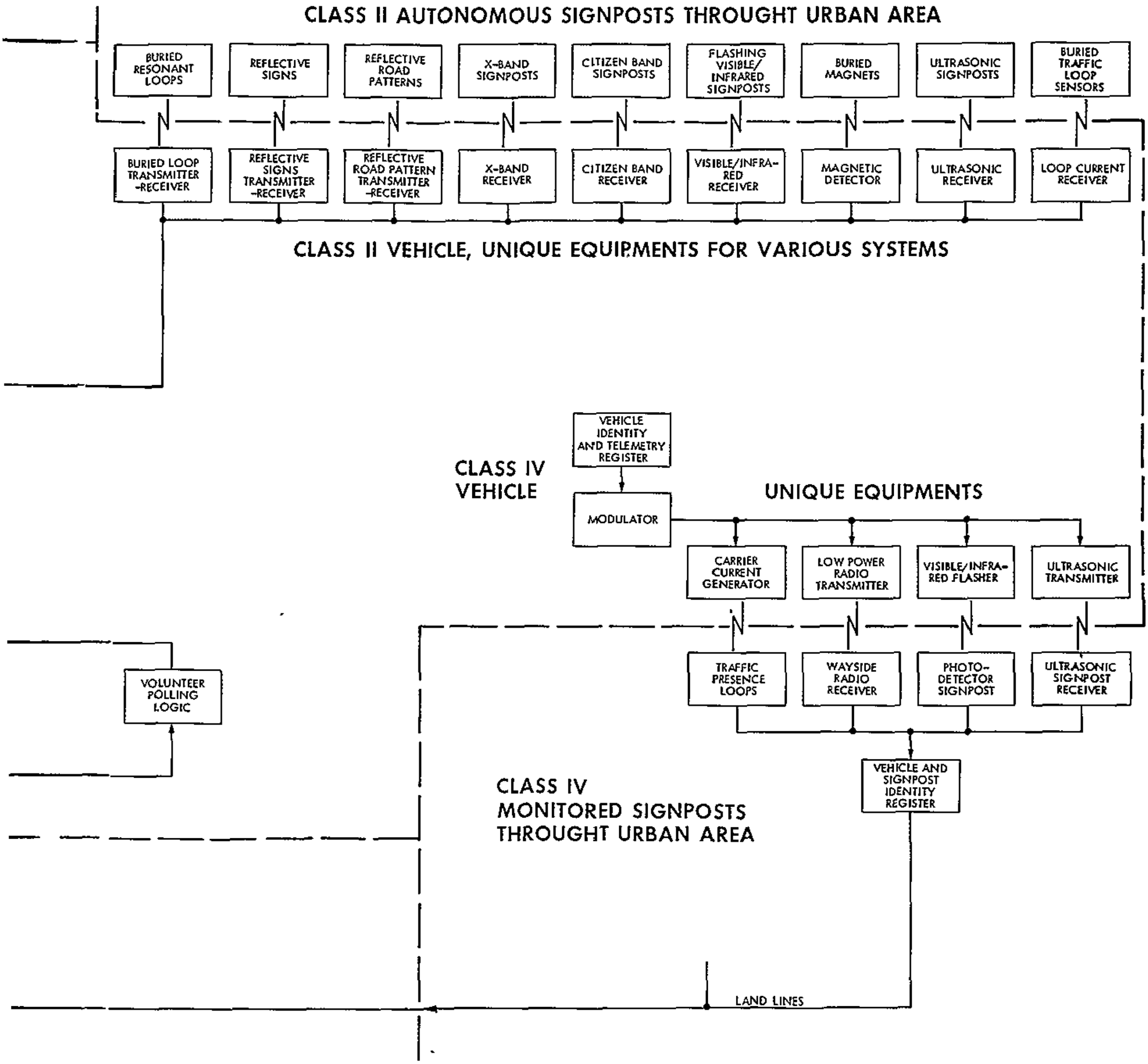


Figure 6. AVM Systems Showing Common and Unique Equipments for Vehicles, Signposts, and Base Stations

Class I, II, and III techniques may use any of the various vehicle polling techniques. 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 minimum 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 is, 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 with 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 radio modification cost is not applicable where a separate radio for AVM signals is selected.

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

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

VEHCOST

AVL COSTS PER VEHICLE IN $

TECHNIQUE	SENSOR	PROC.	RADIO	RAD.MOD	INST	O+M
CLASS I						
KEYBOARD	45	40	1200	50	35	15
STYLUS MAP	2465	35	1200	50	35	25
2-ACCELEROMETERS	400	1000	1200	200	100	100
LASER VELOCIMTR	500	1000	1200	200	135	150
ULTRASONIC VELO	270	300	1200	200	100	150
COMPASS ODOMETER	265	1000	1200	200	20	40
COMPASS LASER VEL	655	1000	1200	200	150	30
CMPSS U-SONIC VEL	385	1000	1200	200	100	90
OMEGA	2500	0	1200	200	80	75
LORAN	2600	0	1200	200	80	75
DECCA	950	0	1200	200	60	75
AM-STATIONS	230	0	1200	200	50	60
DIFF. OMEGA	2500	0	1200	200	30	75
DIFF. LORAN	2600	0	1200	200	30	75
DIFF. AM-STA.	315	0	1200	150	50	60
RELAY OMEGA	375	0	1200	150	80	100
RELAY LORAN	425	0	1200	150	80	100
CLASS II						
BURIED RES. LOOPS	90	0	1200	50	45	15
REFLECTING SIGNS	430	0	1200	50	150	20
REFLECTING ROAD	75	0	1200	50	60	15
X-BAND POST	120	0	1200	50	40	10
HF, VHF POST	105	0	1200	50	40	10
LF POST	100	0	1200	50	45	15
LIGHT I-R POST	95	0	1200	50	75	25
BURIED MAGNETS	50	0	1200	50	45	0
ULTRASONIC POST	85	0	1200	50	35	25
TRAFFIC SENSOR	95	0	1200	50	40	10
CLASS III						
NAR-BAND FM PHASE	60	0	1200	165	40	25
WID-BAND FM PHASE	2875	0	0	30	90	25
PULSE T-O-ARRIVAL	2575	0	0	0	150	25
NOISE CORRELATION	785	0	0	0	100	25
DIRECTION FINDER	35	0	0	0	15	0
CLASS IV						
TRAFFIC LOOPS	80	0	0	0	65	10
WAYSIDE RADIO	75	0	0	0	40	10
PHOTO I-R DETECT	115	0	0	0	70	15
ULTRASONIC DETECT	125	0	0	0	65	15

* Costs as of 1974.

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

FIXEDCOST

TECHNIQUE	EQUIP	INST	O-M	DATA LINK	LINE RENT
	ANL COST PER SITE(OR UNIT) IN $				
CLASS I					
KEYBOARD	0	0	0	0	0
STYLUS MAP	0	0	0	0	0
2-ACCELEROMETERS	0	0	0	0	0
LASER VELOCIMTR	0	0	0	0	0
ULTRASONIC VELO	0	0	0	0	0
COMPASS ODOMETER	0	0	0	0	0
COMPASS LASER VEL	0	0	0	0	0
CMPSS U-SONIC VEL	0	0	0	0	0
OMEGA	0	0	0	0	0
LORAN	0	0	0	0	0
DECCA	0	0	0	0	0
AM-STATIONS	0	0	0	0	0
DIFF. OMEGA	0	0	0	0	0
DIFF. LORAN	0	0	0	0	0
DIFF. AM-STA.	0	0	0	0	0
RELAY OMEGA	0	0	0	0	0
RELAY LORAN	0	0	0	0	0
CLASS II					
BURIED RES. LOOPS	10	17	0	0	0
REFLECTING SIGNS	55	30	5	0	0
REFLECTING ROAD	5	30	25	0	0
X-BAND POST	230	45	15	0	0
HF, UHF POST	130	45	15	0	0
LF POST	125	45	15	0	0
LIGHT I-R POST	100	55	25	0	0
BURIED MAGNETS	2	4	0	0	0
ULTRASONIC POST	85	85	10	0	0
TRAFFIC SENSOR	95	40	0	0	0
CLASS III					
NAR-BAND FM PHASE	4500	500	500	25	5
WID-BAND FM PHASE	9500	1500	500	2070	0
PULSE T-O-ARRIVAL	12000	2500	500	2000	0
NOISE CORRELATION	7500	1500	500	2000	0
DIRECTION FINDER	26000	1500	1200	25	5
CLASS IV					
TRAFFIC LOOPS	165	113	10	13	4
WAYSIDE RADIO	160	113	25	13	4
PHOTO I-R DETECT	170	113	25	13	4
ULTRASONIC DETECT	180	113	25	13	4

* Costs as of 1974.

Additional costs associated with each AVM technique when configured as a system are the base station costs and the vehicle polling system costs, given in Table 4. The base station is 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 radio 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 considered 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, i.e., about 1 four-lane road for each 6 two-lane roads.

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

BASECOST

AVL BASE STATION COSTS IN THOUSANDS OF $

	COMPUTER						SOFTWARE		
TECHNIQUE	SML	MED	LGE	INST	O-M	DISP	SML	MED	LGE
CLASS I									
KEYBOARD	30	40	60	10	100	3	10	20	30
STYLUS MAP	30	40	60	10	100	3	10	20	30
2-ACCELEROMETERS	40	60	80	10	100	3	25	25	50
LASER VELOCIMTR	40	60	30	10	100	3	25	35	50
ULTRASONIC VELO	40	60	80	10	100	3	25	35	50
COMPASS ODOMETER	40	60	80	10	100	3	25	35	50
COMPASS LASER VEL	40	60	80	10	100	3	25	35	50
CMPSS U-SONIC VEL	40	60	80	10	100	3	25	35	40
OMEGA	30	50	70	10	100	3	20	30	40
LORAN	30	50	70	10	100	3	20	30	40
DECCA	30	50	70	10	100	3	20	30	40
AM-STATIONS	30	50	70	10	100	3	20	30	40
DIFF. OMEGA	30	50	70	10	100	3	20	30	40
DIFF. LORAN	30	50	70	10	100	3	20	30	40
DIFF. AM-STA.	30	50	70	10	100	3	20	30	40
RELAY OMEGA	30	50	70	10	100	3	20	30	40
RELAY LORAN	30	50	70	10	100	3	20	30	40
CLASS II									
BURIED RES. LOOPS	30	40	60	10	100	3	10	20	30
REFLECTING SIGNS	30	40	60	10	100	3	10	20	30
REFLECTING ROAD	30	40	60	10	100	3	10	20	30
X-BAND POST	30	40	60	10	100	3	10	20	30
HF, VHF POST	30	40	60	10	100	3	10	20	30
LF POST	30	40	60	10	100	3	10	20	30
LIGHT I-R POST	30	40	60	10	100	3	10	20	30
BURIED MAGNETS	30	40	60	10	100	3	10	20	30
ULTRASONIC POST	30	40	60	10	100	3	10	20	30
TRAFFIC SENSOR	30	40	60	10	100	3	10	20	30
CLASS III									
NAR-BAND FM PHASE	33	80	137	8	100	3	20	40	60
WID-BAND FM PHASE	40	70	70	10	200	3	25	50	100
PULSE T-O-ARRIVAL	100	250	250	10	175	3	35	70	100
NOISE CORRELATION	100	250	250	10	175	3	35	70	100
DIRECTION FINDER	15	30	60	10	150	3	15	30	60
CLASS IV									
TRAFFIC LOOPS	30	40	60	10	100	3	10	20	30
WAYSIDE RADIO	30	40	60	10	100	3	10	20	30
PHOTO I-R DETECT	30	40	60	10	100	3	10	20	30
ULTRASONIC DETECT	30	40	60	10	100	3	10	20	30

*Costs as of 1974.

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 distributed, 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 more 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:

$$\text{Number of narrow-band and pulse sites} = 6 + \frac{\text{area in km}^2}{10}$$

$$\text{Number of wide-band sites} = 4 + \frac{\text{area in km}^2}{40}$$

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 established, 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.

Three estimates 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 equipments. 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-aided 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 vehicle monitors all other vehicles, then the Volunteer technique can only be used on full-duplex (base and vehicle on different frequencies).

1. Synchronous polling. In this technique, each vehicle 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 twice. The digital message rate is set at 1500 bps. Where equivalent RF 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

CONTENTS

FIGURES

FIGURES (CONT)

TABLES

PART ONE. AVM COST BENEFIT INFORMATION BASE

I. PERFORMANCE AND COSTS OF PROVED AVM TECHNIQUES

Costs and performance parameters of 36 operational or proved techniques used for automatic vehicle monitoring (AVM) are described and illustrated in this section. Schemes that are 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 O 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 technique 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.

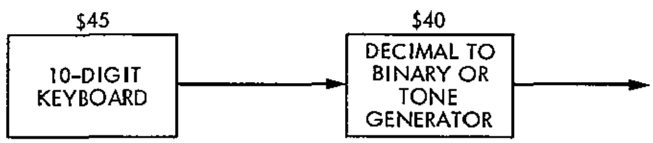
A relatively wide range of options is available to the dispatcher for use with Class O non-automated vehicle monitoring. The simplest visual location aid is just a map on which the assigned beat areas are permanently marked, the dispatcher relying on his memory to locate the vehicles on the map. Numbered magnets or lights may be used which may be updated manually to augment his memory. Elaborate electro-optical 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 available 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 Urban 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 unit. 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.



	W/DIMED	W/O DIMED
VEHICLE EQUIPMENT	0	$85
INSTALLATION	0	$35

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 is 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 x 25 cm (8 x 10 in.) portion of a 7.5-minute U.S. Geological Survey topographic map (scale 1 24000) would cover an area of 6 x 4.8 km (3.6 x 3 mi). If this information were encoded by 5 binary bits (1 in 32) on each axis for a 10-bit location code, then the location could be achieved within a rectangle of about 190 x 150 meters (600 x 500 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 required 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.

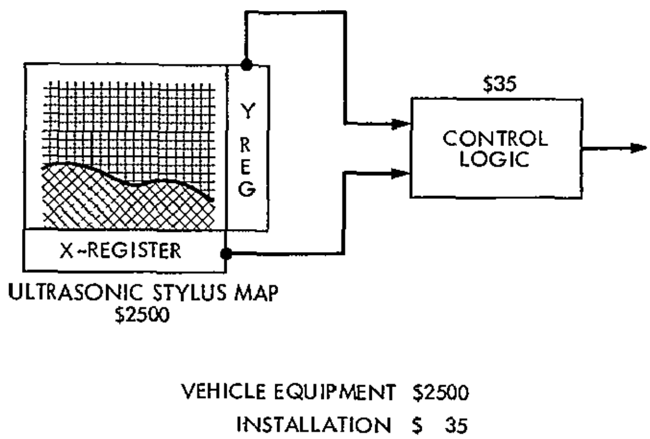


Fig. 1-2. Class I AVM Officer Update Option, Using Stylus Map

2. Kinematic sensors. Changes in vehicle location may be sensed either by accelerometers, velocimeters, 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 m/sec (23 mph) in a 4-lane street about 18 m (60 feet) wide is about the limit of vehicle turning performance. This turn would result in about a 0.8-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 bits/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 maintained in this 0.2-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 velocities are measured at the same point remote from the turning radius, 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 derived 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) indicate that a laser velocimeter's dynamic range is of the order of 2500 to 1 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 m/sec to 2 cm/sec (115 mph to 0.05 mph) could be accommodated, and turning rates of 0.01 radian/sec (0.6 °/s) could be detected. Maximum data bit rates of about 5000/sec for speed and 100/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-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 m/sec (115 mph) will yield a doppler shift of about 10%. If a dynamic range of 2000:1 can be achieved, a minimum velocity of 2.5 cm/sec (0.05 mph) 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 cm/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.

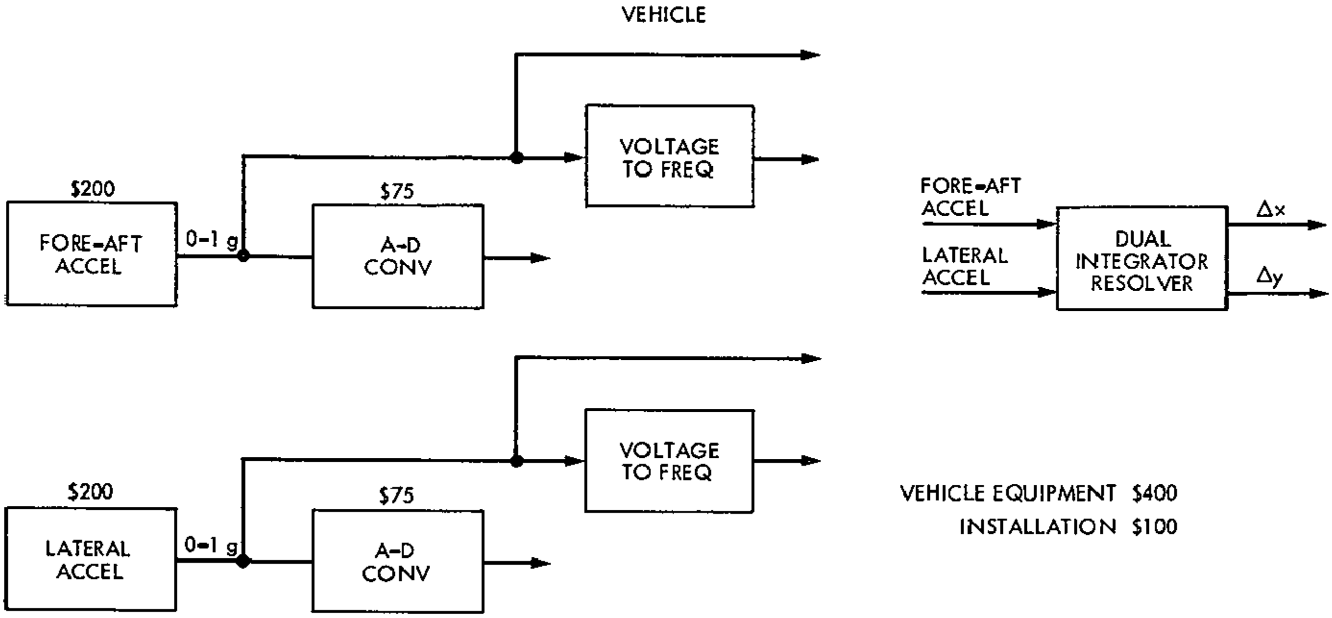


Fig. 1-3. Class I AVM Kinematic Sensor Using Two Accelerometers

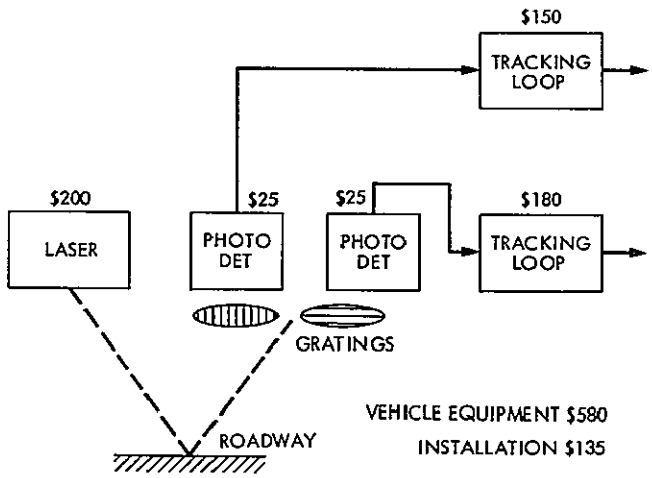


Fig. 1-4. Class I AVM Orthogonal Laser Velocimeter

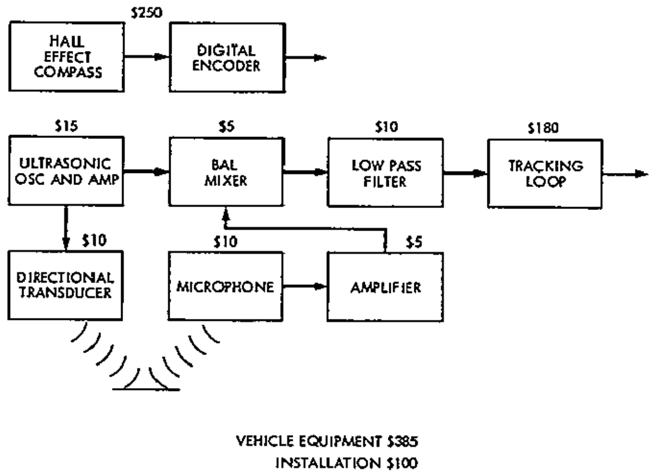


Fig. 1-6. Class I AVM Magnetic Compass with Ultrasonic Velocimeter

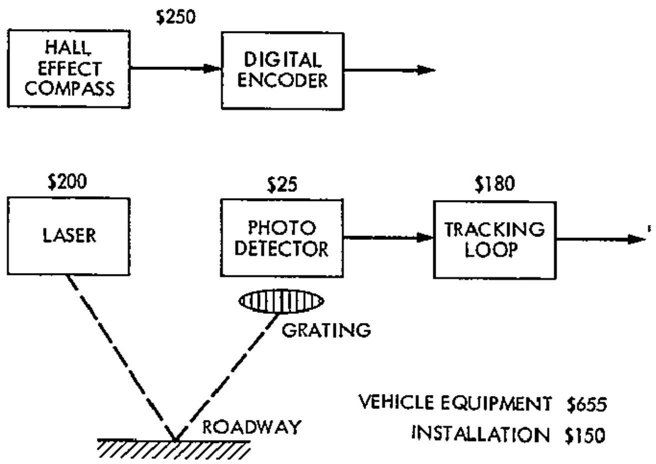


Fig. 1-5. Class I AVM Magnetic Compass with Laser Velocimeter

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 on-board 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.

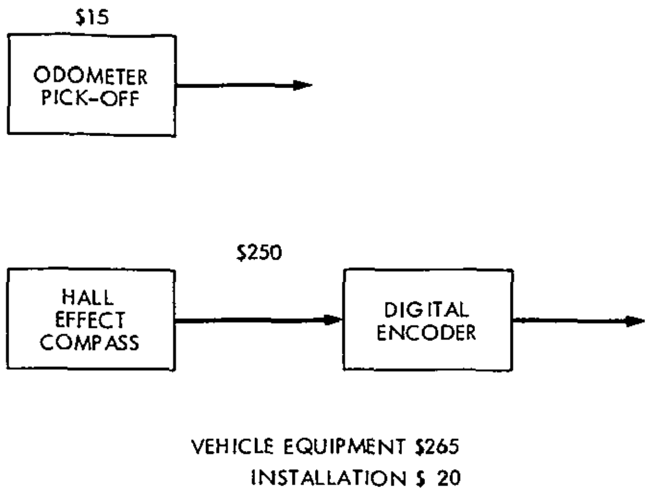


Fig. 1-7. Class I AVM Magnetic Compass with Odometer

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 kHz) time-multiplexed RF signals. The relative phase of the

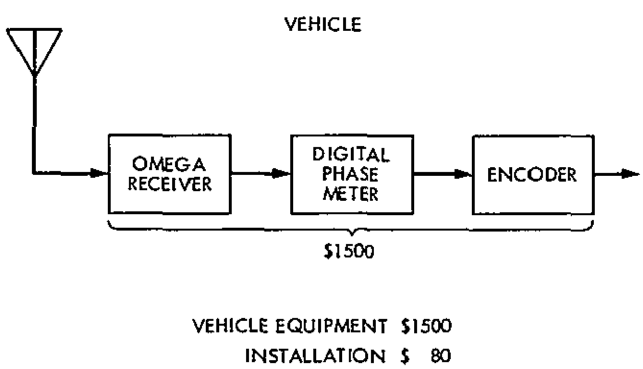


Fig. 1-8. Class I AVM Normal and Differential OMEGA Navigation

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 receiver 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 is a time-consuming operation as each vehicle would have to transmit the entire OMEGA sequence lasting several seconds.

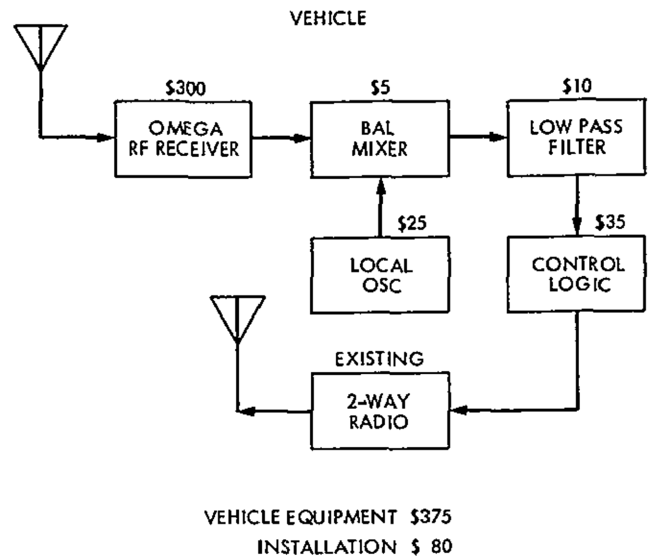


Fig. 1-9. Class I AVM Relay OMEGA Navigation System

c. LORAN. This technique (Fig. 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 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 exists, and each LOP is unique geographically. Differential LORAN also uses fixed site receivers to remove local propagation anomalies.

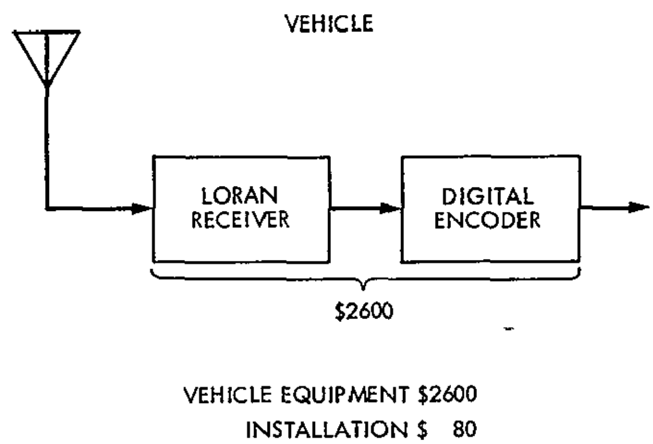


Fig. 1-10. Class I AVM Normal and Differential LORAN Navigation

d. Relay LORAN. In this system (Fig. 1-11), the received signals are retransmitted to a base station for time differencing. Some bandwidth compression 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-kHz bandwidth signals are reduced to 3 to 7 kHz for retransmission. The higher repetition rates of LORAN make relaying more feasible than in OMEGA.

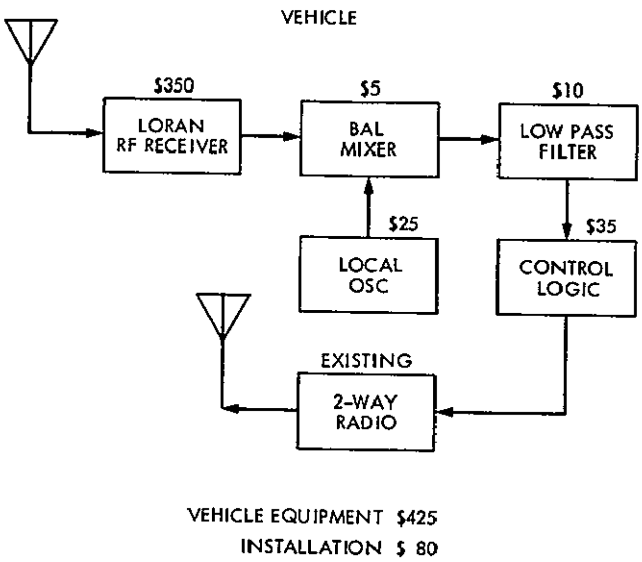


Fig. 1-11. Class I AVM Relay LORAN Navigation System

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 determined by simultaneous reception and comparison of the phase of the signals. Since the LOPs determined by the phase measurements are not unique, special signals are transmitted frequently to enable the determination of the correct one.

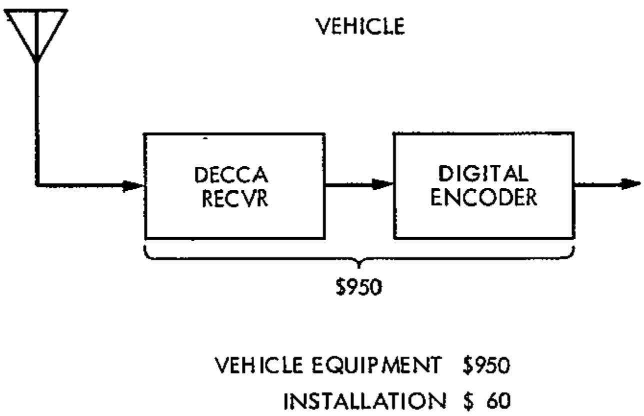


Fig. 1-12. Class I AVM DECCA Navigation System

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 identical frequencies can be made relatively phase coherent. Virtual hyperbolic patterns of navigational 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 detail.

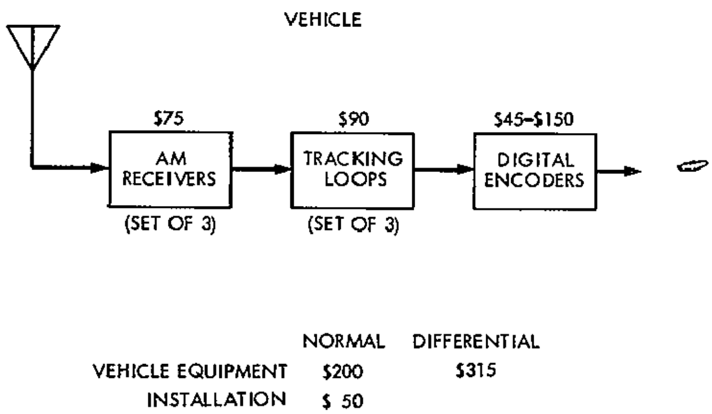
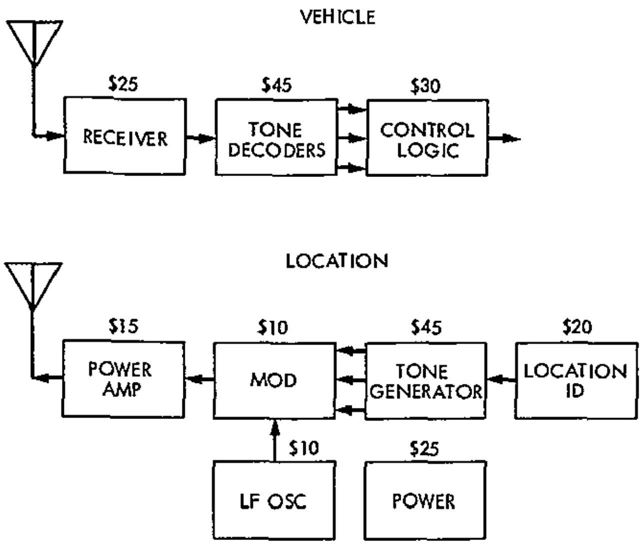


Fig. 1-13. Class I AVM AM Broadcasting Station Navigation Systems

C. Class II AVM: Autonomous Signposts Throughout Urban Area

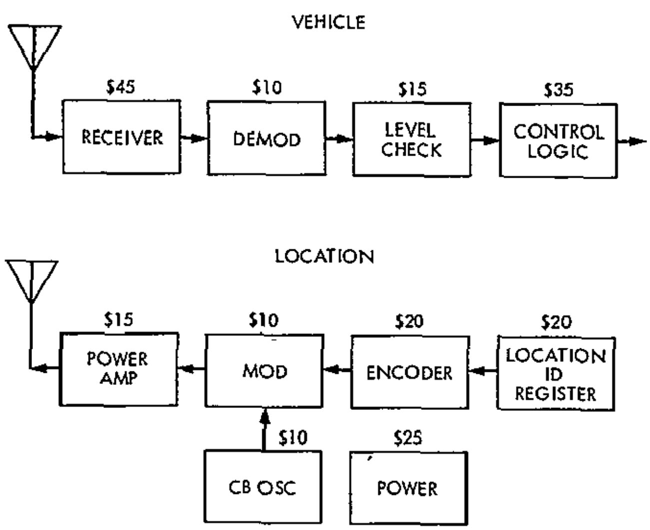
All autonomous signpost location techniques rely on the vehicle coming near or passing over an instrumented geographical location. The instrument, located at an intersection or road segment, is usually a continuously radiating device sending out a uniquely coded message, either radio, light, IR, ultrasound, 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 radius of influence decreases to ensure complete message reception by a fast moving vehicle.



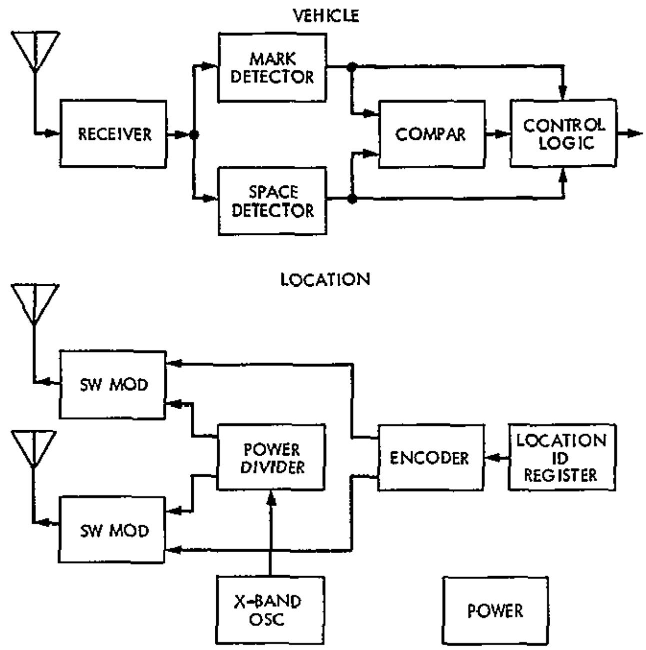
VEHICLE EQUIPMENT $100
INSTALLATION $ 45
FIXED EQUIPMENT $125
INSTALLATION $ 45

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



VEHICLE EQUIPMENT $120
INSTALLATION $ 40
FIXED EQUIPMENT $230
INSTALLATION $ 45

Fig. 1-16. Class II AVM X-Band Wayside Radio Signposts

Since active electronic signposts require some primary power source, difficulties may be encountered in general applications 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 radioisotope 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 desired coverage area. The flashing light approach (Fig. 1-18), either visible or infrared, is 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.

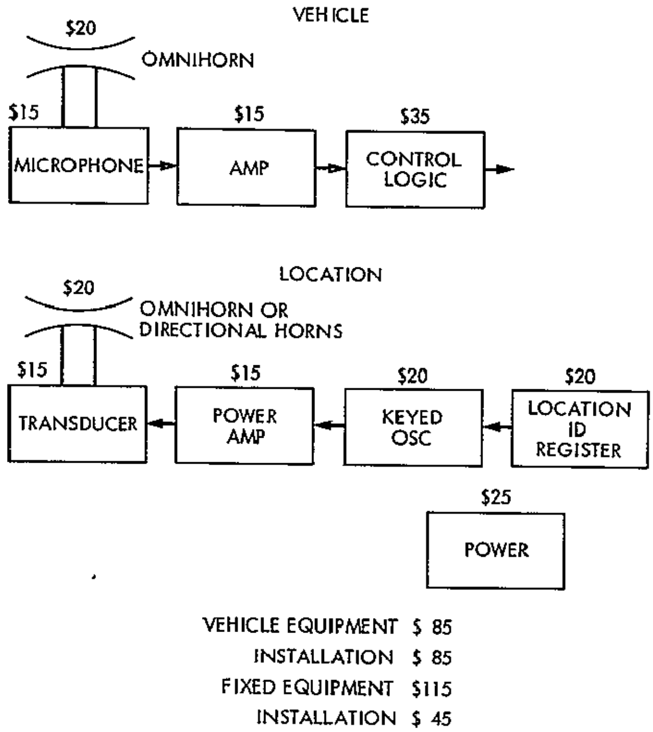


Fig. 1-17. Class II AVM Autonomous Ultrasonic Signposts

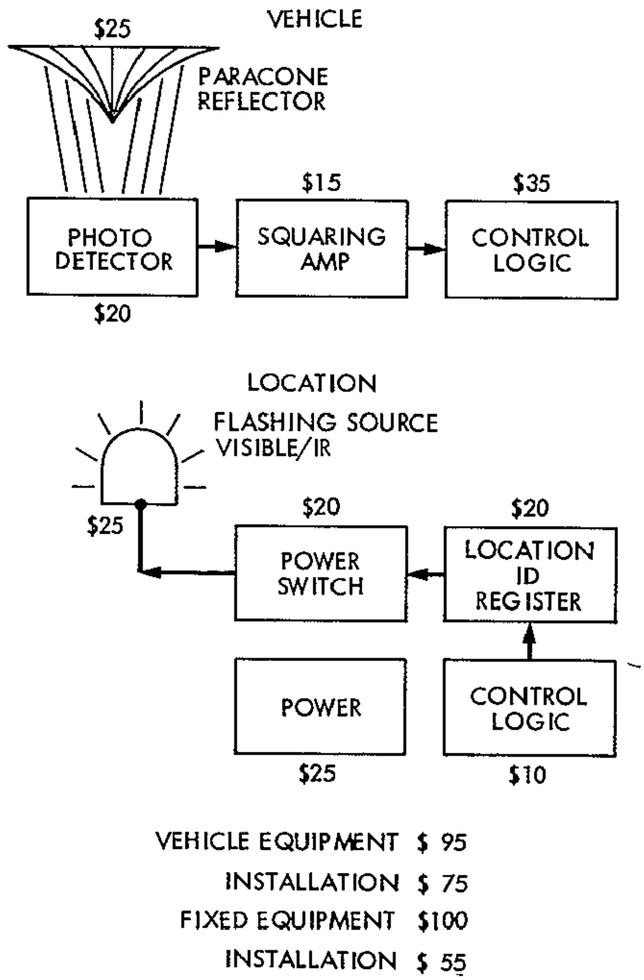


Fig. 1-18. Class II AVM Flashing Visible or IR Light Signposts

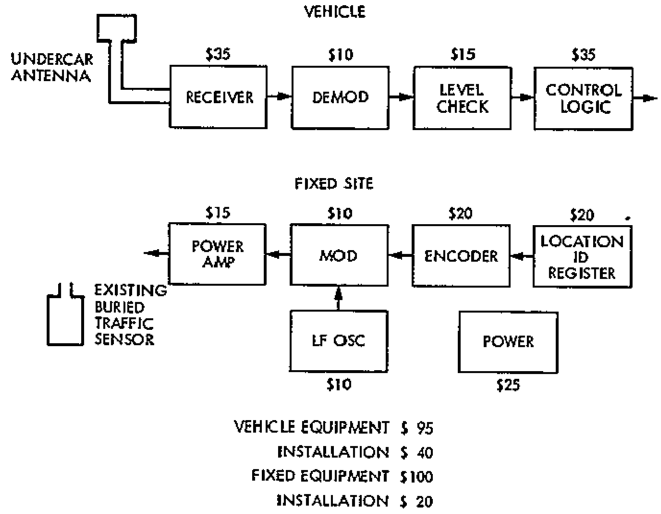


Fig. 1-19. Class II AVM Active Buried Antenna Traffic Sensors

4. Buried magnet autonomous location identifiers. 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 either 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.

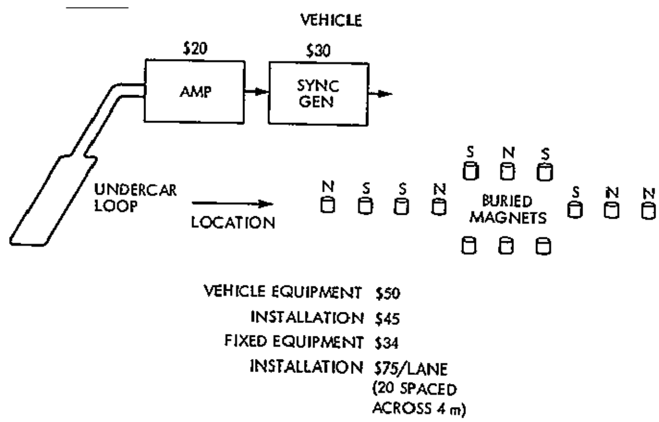


Fig. 1-20. Class II AVM Buried Magnets as Location Identifiers

5. Reflective paint patterns on signposts and roadways. Other passive techniques require that the vehicle continually interrogate the area travelled either by low-frequency RF 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.

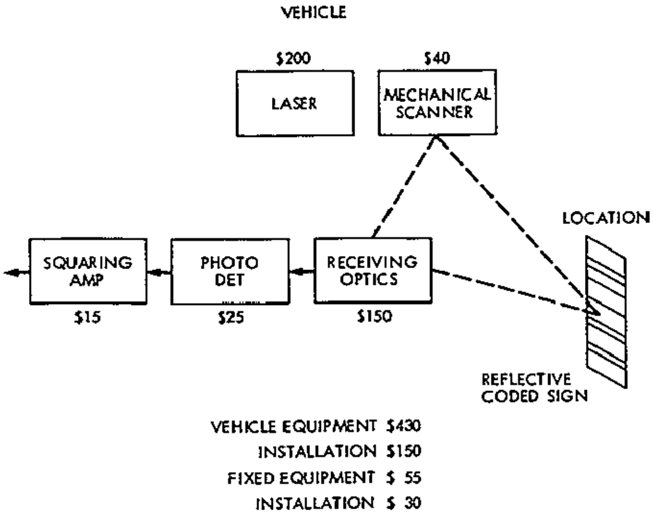


Fig. 1-21. Class II AVM Sensor of Reflective Patterns on Signposts

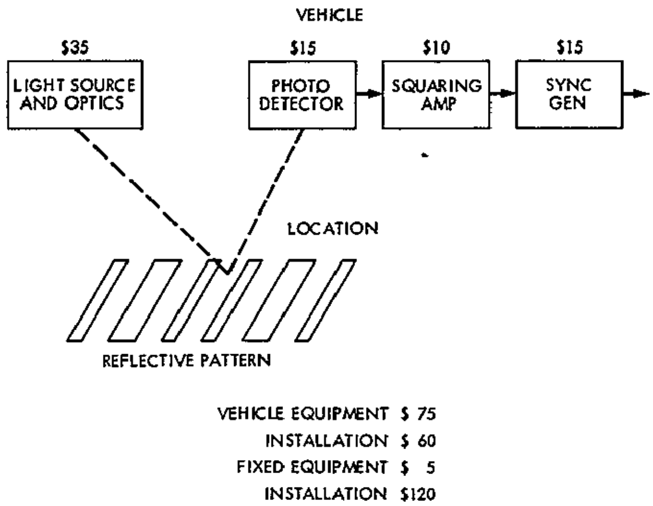


Fig. 1-22. Class II AVM Sensor of Reflective Patterns on Roadway

6. Passive buried loops. The passive buried loop (Fig. 1-23) 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 buried 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 theta-theta (angle-angle) types with sparsely distributed RF sites primarily intended for medium or small urban area coverage, 7 km (4 mi) to 11 km (7 mi) radius.

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

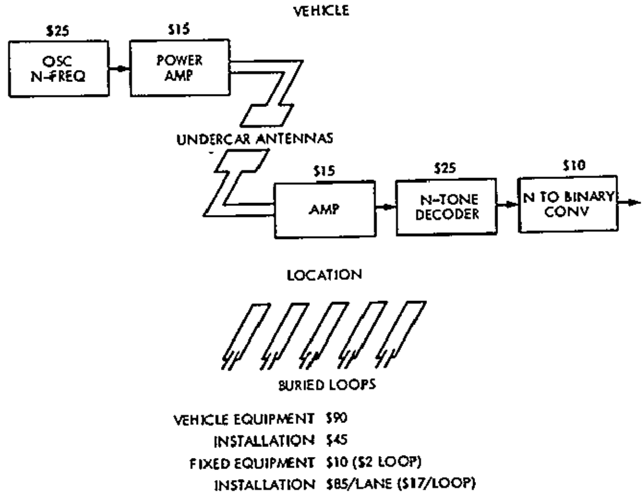


Fig. 1-23 Class II AVM Sensor of Passive Buried Resonant Loops

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.

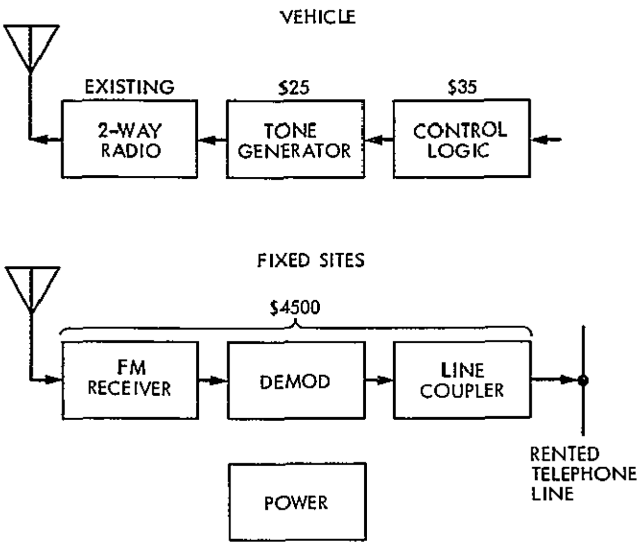
Hyperbolic trilateration methods tested have used either a pulsed (or keyed) carrier from the vehicle or an audio-tone frequency modulating a carrier. The pulse systems measure the TOA of the signal and establish the range differences directly. The tone trilateration systems measure the relative phase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

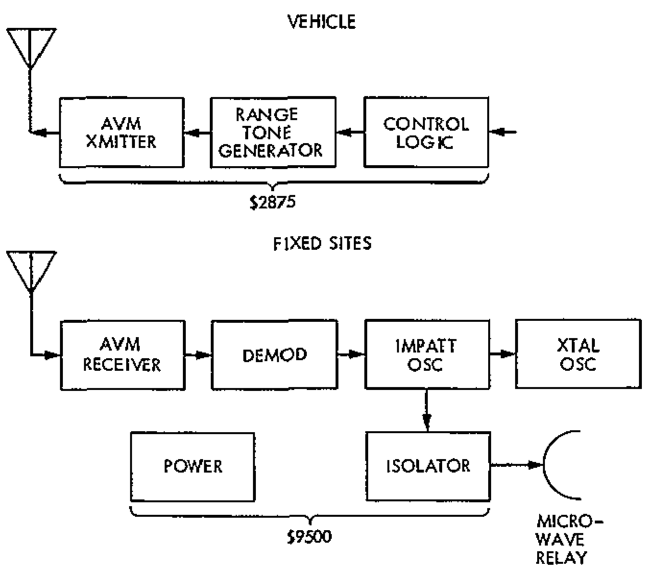
2. Triangulation Systems. The direction finding methods proposed would measure the azimuth angle of the vehicle signal at several fixed sites (Fig. 1-28). The intersection of the extension of these bearing angles would be the position of the vehicle. Multipath in this method would probably cause uncertainty 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, wide-band phase, and noise modulation TOA methods would require an additional AVM transmitter.



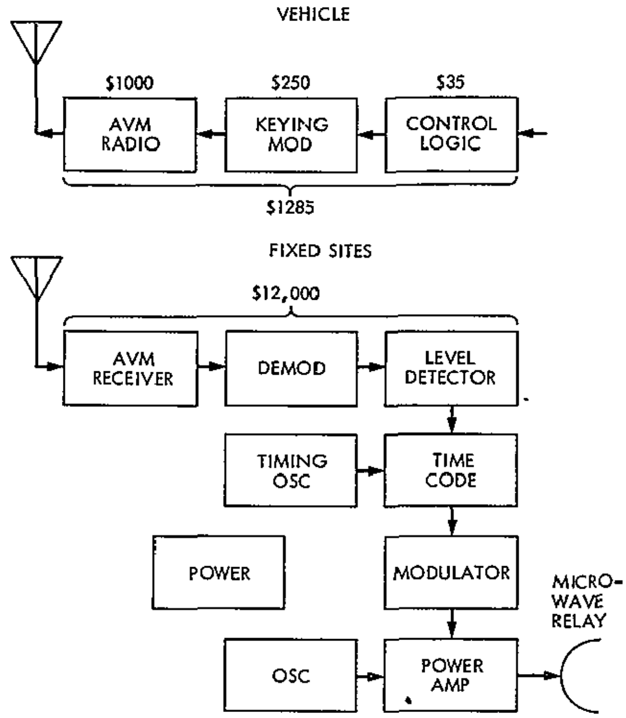
VEHICLE EQUIPMENT $ 60
INSTALLATION $ 40
FIXED SITE EQUIPMENT $4,500
INSTALLATION $ 500

Fig. 1-24. Class III AVM Narrow-Band FM Phase TOA Trilateration



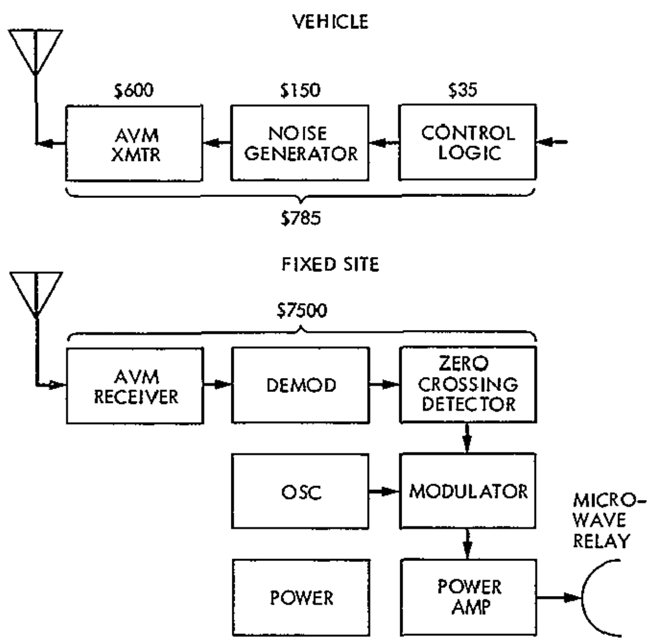
VEHICLE EQUIPMENT $2875 (CUBIC)
INSTALLATION $ 90
FIXED SITE EQUIPMENT $9500
INSTALLATION $1500

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. 1-27. Class III AVM Noise Correlation TOA Trilateration

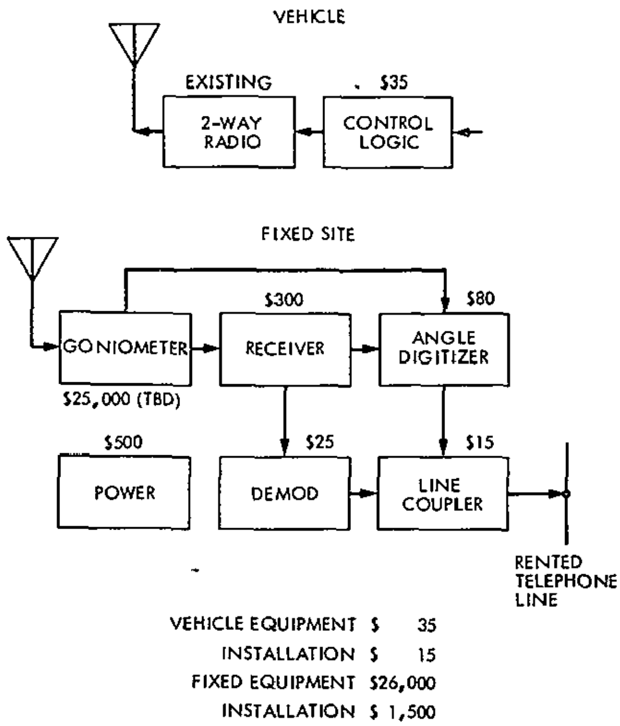


Fig. 1-28. Class III AVM Direction Finding from Special RF Sites

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. 1-29) is maintained, 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 lines for police and fire use. Since individual lines 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 received 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. 1-30) 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 replaced 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.

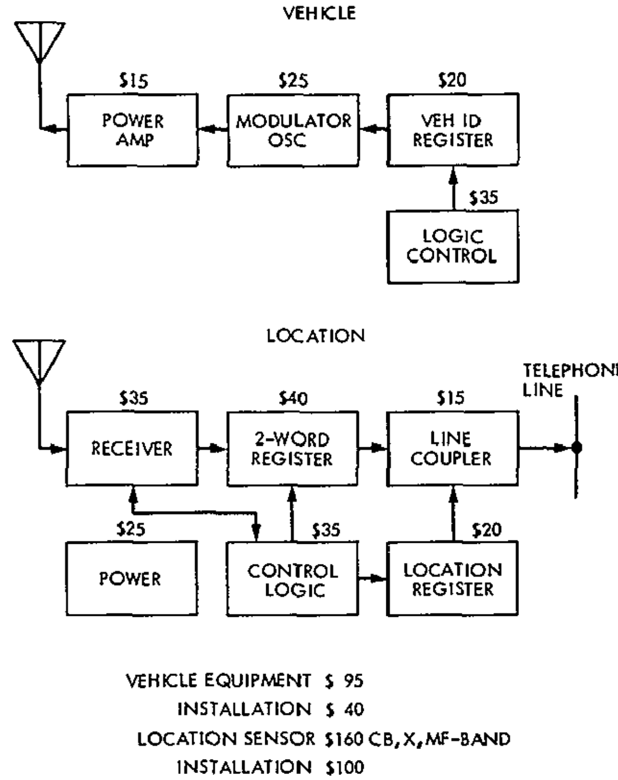


Fig. 1-29. Class IV AVM Monitored Wayside Radio Receivers

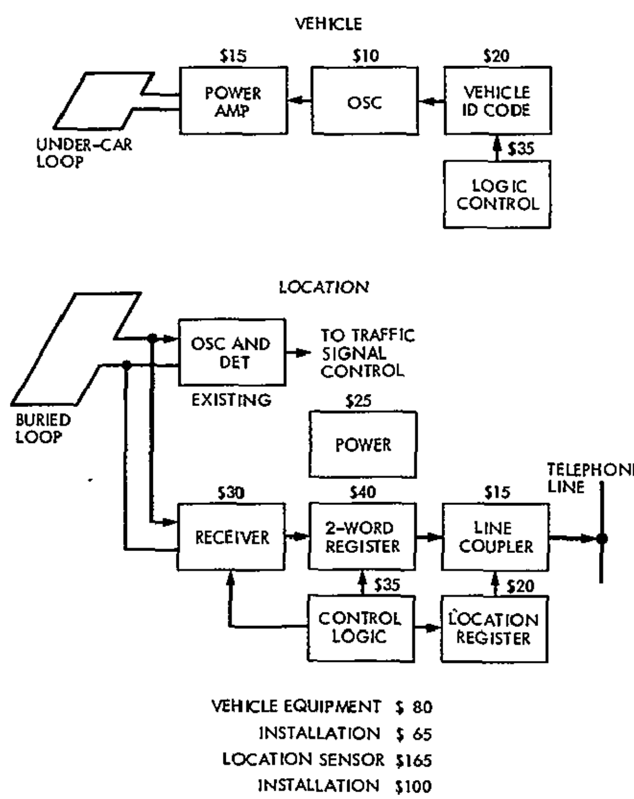


Fig. 1-30. Class IV AVM Monitored Traffic Presence Sensors

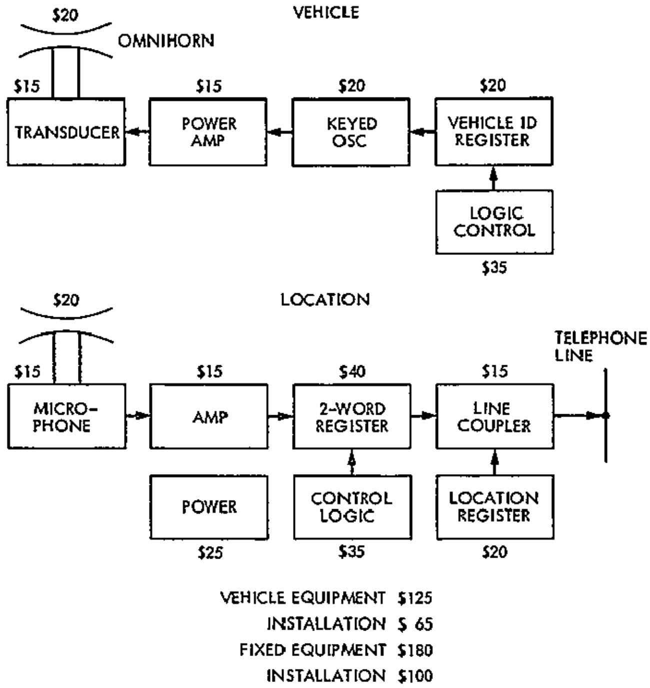


Fig. 1-31. Class IV AVM Monitored Ultrasonic Wave Receptors

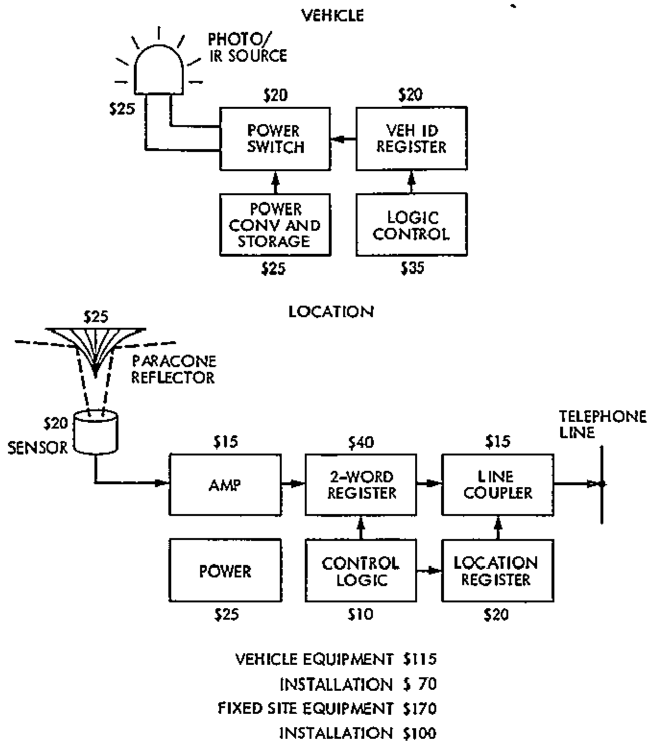


Fig. 1-32. Class IV AVM Monitored Photo or IR Detectors

II. VEHICLE POLLING AND 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 low-density 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 technique 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 within 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 vehicles are to respond in the polling epoch.

2. Synchronous with command capability. This technique allows the base station to modify the position of each vehicle in the polling sequence. The additional functional elements for the command option are shown in Fig. 1-34 connected by dashed lines to the elements required for synchronous polling.

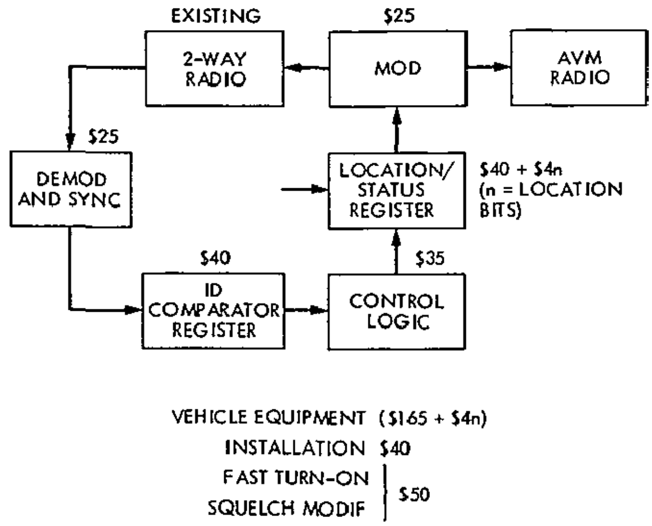


Fig 1-33. Vehicle Synchronized Polling for AVM Classes I, II, III

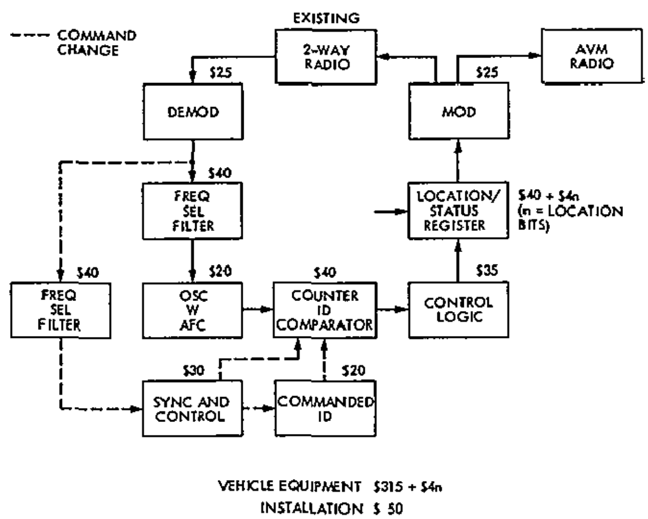


Fig. 1-34. Vehicle Commanded Polling for AVM Classes I, II, III.

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 vehicles from dominating the channel.

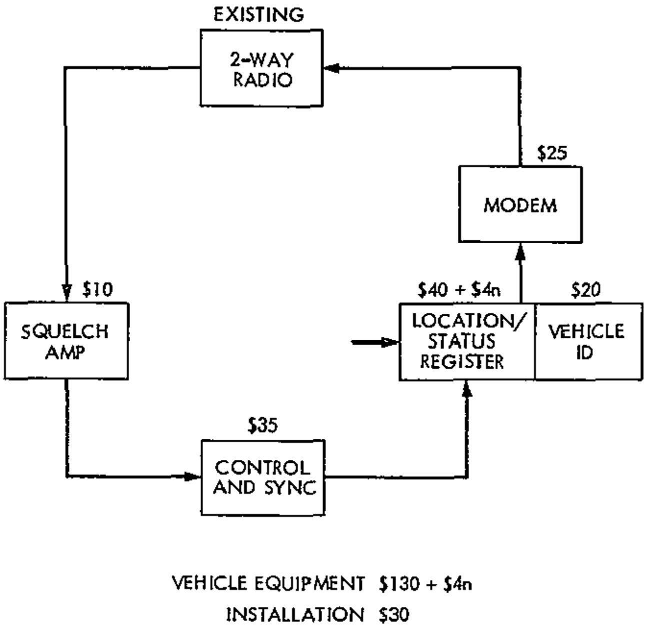


Fig. 1-35. Vehicle Volunteer Polling for AVM Class II Systems

B. Vehicle Polling and RF Link Evaluations

The three vehicle polling techniques: Synchronous (SYN), Volunteer (VOL), and Random (RAND) or commanded were evaluated with both a simple one-time radio message transmission and with redundant transmission, where every message is sent twice. In all cases, the digital message rate is set at 1500 bps. Where equivalent 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 RF 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 circuits relative to half-duplex with electromechanical 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 maximum 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, transponder 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

CARS PER SECOND PER RF CHANNEL WITH DIFFERENT POLLING

TECHNIQUE CLASS I	THEO MAX	SIMPLE SYN	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYN	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	137	137	72	72	69	36	36
STYLUS MAP	84	84	54	54	42	27	27
2-ACCELEROMETERS	108	108	63	63	54	32	32
LASER VELOCIMTR	94	94	58	58	47	29	29
ULTRASONIC VELO	108	108	63	63	54	32	32
COMPASS/ODOMETER	108	108	63	63	54	32	32
COMPASS/LASER VEL	108	108	63	63	54	32	32
CMPSS/U-SONIC VEL	108	108	63	63	54	32	32
OMEGA	56	56	41	41	28	21	21
LORAN	47	47	36	36	24	18	18
DECCA	50	50	38	38	25	19	19
AM-STATIONS	125	125	69	69	63	35	35
DIFF OMEGA	56	56	41	41	28	21	21
DIFF LORAN	47	47	36	36	24	13	18
DIFF AM-STA	58	58	42	42	29	21	21
RELAY OMEGA	1	1	1	1	1	1	1
RELAY LORAN	3	3	3	3	2	2	2

TECHNIQUE CLASS II	THEO MAX SM/LG	SIMPLE SYN SM/LG	SIMPLE VOL SM/LG	SIMPLE RAND SM/LG	REDUNDANT SYN SM/LG	REDUNDANT VOL SM/LG	REDUNDANT RAND SM/LG
BURIED RES LOOPS	150	150	108	108	75	54	54
	34	34	54	54	42	27	27
REFLECTING SIGNS	150	150	108	108	75	54	54
	34	34	54	54	42	27	27
REFLECTING ROAD	150	150	108	108	75	54	54
	34	34	54	54	42	27	27
X-BAND POST	167	167	116	116	84	58	58
	39	39	56	56	45	28	28
HF, VHF POST	215	215	137	137	108	69	69
	108	108	60	60	50	30	30
LF POST	167	167	116	116	84	58	58
	39	39	56	56	45	28	28
LIGHT/I-R POST	167	167	116	116	84	58	58
	39	39	56	56	45	28	28
BURIED MAGNETS	150	150	108	108	75	54	54
	34	34	54	54	42	27	27
ULTRASONIC POST	167	167	116	116	84	58	58
	39	39	56	56	45	28	28
TRAFFIC SENSOR	150	150	108	108	75	54	54
	34	34	54	54	42	27	27

CLASS III — CARS PER SECOND

TECHNIQUE	MIN RF CHANNELS	SIMPLE SYNC	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT RAND
NAR-BAND FM PHASE	1	67	47	34	24
MID-BAND FM PHASE	4	400	110	200	55
PULSE T-O-ARRIVAL	400	10000	10000	10000	10000
NOISE CORRELATION	200	1000	1000	1000	1000
DIRECTION FINDER	1	5	5	[illegible]	3

Table 1-2. Vehicles Polled/Second/RF Channel For 0.01-Sec Turn-On

CARS PER SECOND PER RF CHANNEL WITH DIFFERENT POLLING

TECHNIQUE CLASS I	THEO MAX	SIMPLE SYN	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYN	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	137	58	42	30	41	27	15
STYLUS MAP	84	46	35	26	30	22	13
2 ACCELEROMETERS	108	52	39	28	35	24	14
LASER VELOCIMTR	94	49	37	27	32	24	14
ULTRASONIC VELO	108	52	39	28	35	24	14
COMPASS/ODOMETER	108	52	39	28	35	24	14
COMPASS/LASER VEL	108	52	39	28	35	24	14
CMPSS/U-SONIC VEL	108	52	39	28	35	24	14
OMEGA	56	36	29	23	22	17	12
LORAN	47	32	27	21	19	16	11
DECCA	50	34	28	22	20	16	11
AM-STATIONS	125	56	41	29	34	26	15
DIFF OMEGA	56	36	29	23	22	17	12
DIFF LORAN	47	32	27	21	19	16	11
DIFF AM-STA	58	37	30	23	23	18	12
RELAY OMEGA	1	1	1	1	1	1	1
RELAY LORAN	3	3	3	3	2	2	2

TECHNIQUE CLASS II	THEO MAX SM/LG	SIMPLE SYN SM/LG	SIMPLE VOL SM/LG	SIMPLE RAND SM/LG	REDUNDANT SYN SM/LG	REDUNDANT VOL SM/LG	REDUNDANT RAND SM/LG
BURIED RES LOOPS	150	60	52	35	43	35	18
	34	46	35	26	30	22	13
REFLECTING SIGNS	150	60	52	35	43	35	18
	34	46	35	26	30	22	13
REFLECTING ROAD	150	60	52	35	43	35	18
	34	46	35	26	30	22	13
X-BAND POST	167	63	54	35	46	37	18
	39	47	36	27	31	22	14
HF, VHF POST	215	69	58	37	52	41	19
	108	50	38	28	34	24	14
LF POST	167	63	54	35	46	37	18
	39	47	36	27	31	22	14
LIGHT/I-R POST	167	63	54	35	46	37	18
	39	47	36	27	31	22	14
BURIED MAGNETS	150	60	52	35	43	35	18
	34	46	35	26	30	22	13
ULTRASONIC POST	167	63	54	35	46	37	18
	39	47	36	27	31	22	14
TRAFFIC SENSOR	150	60	52	35	43	35	18
	34	46	35	26	30	22	13

CLASS III — CARS PER SECOND

TECHNIQUE	MIN RF CHANNELS	SIMPLE SYNC	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT RAND
NAR-BAND FM PHASE	1	40	32	25	17
WID-BAND FM PHASE	4	30	50	67	36
PULSE T-O-ARRIVAL	400	10000	10000	10000	10000
NOISE CORRELATION	200	1000	1000	1000	1000
DIRECTION FINDER	1	5	5	3	3

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

CARS PER SECOND PER RF CHANNEL WITH DIFFERENT POLLING

TECHNIQUE CLASS I	THEO MAX	SIMPLE SYN	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYN	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	137	27	23	14	23	18	7
STYLUS MAP	34	24	21	13	19	17	7
2-ACCELEROMETERS	100	26	22	14	21	17	7
LASER VELOCIMTR	94	25	22	13	20	16	7
ULTRASONIC VELO	108	26	22	14	21	17	7
COMPASS/ODOMETER	108	26	22	14	21	17	7
COMPASS/LASER VEL	108	26	22	14	21	17	7
CMPSS/U-SONIC VEL	108	26	22	14	21	17	7
OMEGA	56	21	19	12	16	13	6
LORAN	47	20	13	12	14	12	6
DECCA	50	20	18	12	15	12	6
AM-STATIONS	125	27	23	14	22	17	7
DIFF OMEGA	56	21	19	12	16	13	6
DIFF LORAN	47	20	13	12	14	12	6
DIFF. AM-STA	53	22	19	12	16	13	6
RELAY OMEGA	1	1	1	1	1	1	1
RELAY LORAN	3	3	3	3	2	2	2

TECHNIQUE CLASS II	THEO MAX SM/LG	SIMPLE SYN SM/LG	SIMPLE VOL SM/LG	SIMPLE RAND SM/LG	REDUNDANT SYN SM/LG	REDUNDANT VOL SM/LG	REDUNDANT RAND SM/LG
BURIED RES LOOPS	150	28	26	15	24	21	8
	84	24	21	13	19	15	7
REFLECTING SIGNS	150	28	26	15	24	21	8
	84	24	21	13	19	15	7
REFLECTING ROAD	150	28	26	15	24	21	8
	84	24	21	13	19	15	7
X-BAND POST	167	28	26	15	24	22	8
	89	25	21	13	19	16	7
HF, VHF POST	215	29	27	15	26	23	8
	108	25	22	14	20	16	7
LF POST	167	28	26	15	24	22	8
	89	25	21	13	19	16	7
LIGHT/I-R POST	167	28	26	15	24	22	8
	89	25	21	13	19	16	7
BURIED MAGNETS	150	28	26	15	24	21	8
	84	24	21	13	19	15	7
ULTRASONIC POST	167	28	26	15	24	22	8
	89	25	21	13	19	16	7
TRAFFIC SENSOR	150	28	26	15	24	21	8
	84	24	21	13	19	15	7

CLASS III — CARS PER SECOND

TECHNIQUE	MIN RF CHANNELS	SIMPLE SYNC	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT RAND
NAR-BAND FM PHASE	1	23	20	17	14
WID-BAND FM PHASE	4	31	26	29	21
PULSE T-O-ARRIVAL	400	10000	10000	10000	10000
NOISE CORRELATION	200	1000	1000	1000	1000
DIRECTION FINDER	1	5	5	3	3

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

CARS PER SECOND PER RF CHANNEL WITH DIFFERENT POLLING

TECHNIQUE CLASS I	THEO MAX	SIMPLE SYN	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYN	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	137	10	9	5	9	8	3
STYLUS MAP	34	9	9	5	9	8	3
2-ACCELEROMETERS	108	10	9	5	9	8	3
LASER VELOCIMTR	94	10	9	5	9	8	3
ULTRASONIC VELO	108	10	9	5	9	8	3
COMPASS/ODOMETER	108	10	9	5	9	8	3
COMPASS/LASER VEL	108	10	9	5	9	8	3
CMPSS/U-SONIC VEL	108	10	9	5	9	8	3
OMEGA	56	9	9	5	8	7	3
LORAN	47	9	8	5	8	7	3
DECCA	50	9	8	5	8	7	3
AM-STATIONS	125	10	9	5	9	8	3
DIFF OMEGA	56	9	9	5	8	7	3
DIFF LORAN	47	9	8	5	8	7	3
DIFF AM-STA	56	9	9	5	8	7	3
RELAY OMEGA	1	1	1	1	1	1	1
RELAY LORAN	3	3	3	2	2	2	1

TECHNIQUE CLASS II	THEO MAX SM/LG	SIMPLE SYN SM/LG	SIMPLE VOL SM/LG	SIMPLE RAND SM/LG	REDUNDANT SYN SM/LG	REDUNDANT VOL SM/LG	REDUNDANT RAND SM/LG
BURIED RES LOOPS	150	10	10	5	9	9	3
	84	9	9	5	9	8	3
REFLECTING SIGNS	150	10	10	5	9	9	3
	84	9	9	5	9	8	3
REFLECTING ROAD	150	10	10	5	9	9	3
	84	9	9	5	9	9	3
X-BAND POST	167	10	10	5	9	9	3
	89	9	9	5	9	8	3
HF, VHF POST	215	10	10	5	10	9	3
	100	10	9	5	9	8	3
LF POST	167	10	10	5	9	9	3
	89	9	9	5	9	8	3
LIGHT/I-R POST	167	10	10	5	9	9	3
	89	9	9	5	9	8	3
BURIED MAGNETS	150	10	10	5	9	9	3
	84	9	9	5	9	8	3
ULTRASONIC POST	167	10	10	5	9	9	3
	89	9	9	5	9	8	3
TRAFFIC SENSOR	150	10	10	5	9	9	3
	84	9	9	5	9	8	3

CLASS III — CARS PER SECOND

TECHNIQUE	MIN RF CHANNELS	SIMPLE SYNC	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT RAND
NAR-BAND FM PHASE	1	9	9	8	7
WID-BAND FM PHASE	4	10	10	10	9
PULSE T-O-ARRIVAL	400	10000	10000	10000	10000
NOISE CORRELATION	200	1000	1000	1000	1000
DIRECTION FINDER	1	4	4	2	2

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

CARS PER SECOND PER RF CHANNEL WITH DIFFERENT POLLING

TECHNIQUE CLASS I	THEO MAX	SIMPLE SYN	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYN	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	137	4	4	2	4	4	1
STYLUS MAP	34	4	4	2	4	3	1
2-ACCELEROMETERS	108	4	4	2	4	4	1
LASER VELOCIMTR	94	4	4	2	4	4	1
ULTRASONIC VELO	108	4	4	2	4	4	1
COMPASS/ODOMETER	108	4	4	2	4	4	1
COMPASS/LASER VEL	108	4	4	2	4	4	1
CMPSS/U-SONIC VEL	108	4	4	2	4	4	1
OMEGA	56	4	4	2	3	3	1
LORAN	47	4	4	2	3	3	1
DECCA	50	4	4	2	3	3	1
AM-STATIONS	125	4	4	2	4	4	1
DIFF OMEGA	56	4	4	2	3	3	1
DIFF LORAN	47	4	4	2	3	3	1
DIFF AM-STA	56	4	4	2	3	3	1
RELAY OMEGA	1	1	1	1	1	1	1
RELAY LORAN	3	2	2	2	2	2	1

TECHNIQUE CLASS II	THEO MAX SM/LG	SIMPLE SYN SM/LG	SIMPLE VOL SM/LG	SIMPLE RAND SM/LG	REDUNDANT SYN SM/LG	REDUNDANT VOL SM/LG	REDUNDANT RAND SM/LG
BURIED RES LOOPS	150	4	4	2	4	4	1
	84	4	4	2	4	3	1
REFLECTING SIGNS	150	4	4	2	4	4	1
	84	4	4	2	4	3	1
REFLECTING ROAD	150	4	4	2	4	4	1
	84	4	4	2	4	3	1
X-BAND POST	167	4	4	2	4	4	1
	89	4	4	2	4	3	1
HF, VHF POST	215	4	4	2	4	4	1
	108	4	4	2	4	3	1
LF POST	167	4	4	2	4	4	1
	89	4	4	2	4	3	1
LIGHT/I-R POST	167	4	4	2	4	4	1
	89	4	4	2	4	3	1
BURIED MAGNETS	150	4	4	2	4	4	1
	84	4	4	2	4	3	1
ULTRASONIC POST	167	4	4	2	4	4	1
	89	4	4	2	4	3	1
TRAFFIC SENSOR	150	4	4	2	4	4	1
	84	4	4	2	4	3	1

CLASS III — CARS PER SECOND

TECHNIQUE	MIN RF CHANNELS	SIMPLE SYNC	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT RAND
NAR-BAND FM PHASE	1	4	4	4	3
WID-BAND FM PHASE	4	4	4	4	4
PULSE T-O-ARRIVAL	400	10000	10000	10000	10000
NOISE CORRELATION	200	1000	1000	1000	1000
DIRECTION FINDER	1	2	2	2	2

Message lengths of most vehicle polling techniques are about 20 bits or occupy about 15 milliseconds or less of transmission time 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 finding, 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 vicinity.

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 technique 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 availability of RF channels, determines the delays in receiving vehicle data at the base, which in turn affects the AVM system accuracy.

Another parameter is the "fix" time required for the vehicle to receive or generate whatever raw data is required for the new location to be determined elsewhere, which is primarily technique dependent. Similarly the interval between successive messages from the vehicle is also technique 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 radius, 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 either 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 is inappropriate, and the term radius is used.

2. Radius. In Class II, III, and IV AVM systems, this radius 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 signpost will receive at least two location messages while moving at a speed of 50 m/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 aids, the figure is either 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. URBAN 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 physical parameters 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. City Shape. One characteristic of the model cities that is 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, railway, or coastal harbor usually results in one dimension being significantly greater than the other. The choice 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 km^2 (4, 40, and 400 mi^2), which compare with Montclair and Monterey Park as the smallest cities, Anaheim, Pasadena, and Long Beach as the medium 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/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

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

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

Parameter	Small	Medium	Large
Area, km^2	10	100	1000
Dimensions, km	2.2 × 4.5	7.1 × 14.2	22.3 × 44.7
Vehicles, patrol/total	5/10	50/100	500/1000
Intersections*	350	3500	35000
Road segments × lanes	1600	16800	168000
Road distance, km	125	1245	12450
Telephone lines, km	83	828	8275
Population	30,000	300,000	3,000,000

*Based on 25/75% ratio of 50/30 blocks/km^2 in the urban area.

5. Intersections. The number of intersections in each city is based on two business area street densities. They are based on actual measurements of randomly selected areas of the UGAC cities, and the values assumed are $30/km^2$ for 75% of the area and $50/km^2$ 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. Building 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 particular technique.

9. Radio. The only information sent from the vehicle in this comparison is that required for location, either as a binary message or equivalent RF bandwidth for the Class I, II, and III systems. Radio modifications are also assumed to enable automatic message transmission. Additionally, 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, medium, 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-maintenance (O-M) cost with the result that there is a great similarity 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 substantially higher than those of any other Class II technique because of installation costs. The more sparsely distributed RF posts, either HF or VHF, do not impact the total cost to the extent of the techniques which use a post at each intersection. In the Class III techniques that require pulse or wideband equipment, the vehicular equipment 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 techniques systems costs are reducible 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 techniques 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

```
APEA IS 4 SQUAPE MILES.

EAST WEST DISTANCE IS 1.4 MILES.

NOPTH SOUTH DISTANCE IS 2.: MILES.

TOTAL ROAD MILEAGE IS 77 MILES.

THE NUMBEP OF INTERSECTIONS IS 350:

THE ESTIMATED NUMBEP OF ROAD SEGMENTS IS 700.

THEPE APE 10 CAPS IN THE FLEET

AND THERE APE 0 MOTOPCYCLES.

THE NUMBEP OF VEHICLES ON EACH SHIFT IS:

    FIPST SHIFT MAX. 5

    FIRST SHIFT MIN. 5

    SECOND SHIFT MAX. 5

    SECOND SHIFT MIN. 5

    THIRD SHIFT MAX 5

    THIRD SHIFT MIN. 5

THE CITY WOULD PEQUIRE 4 WIDE-BAND OR

PULSE T-O-A ANTENNA SITES AND 6 NARPOW

BAND ANTENNA SITES WITH 7 AND 3 MILE COVEPAGE PADII.
```

Table 1-9. Small Model City
AVM Cost Summary

SMALL MODEL CITY
CLASS I

TECHNIQUE	CARS	SITES	BASE	INST	O-M	POL	SYNC	RANDOM
		THOUSANDS OF $					TOTALS	
KEYBOARD	2	0	44	11	101	158	156	156
STYLUS MAP	26	0	44	11	101	182	181	181
2-ACCELEROMETERS	16	0	68	11	101	198	200	288
LASER VELOCIMTR	18	0	69	12	102	202	204	203
ULTRASONIC VELO	13	0	69	11	102	196	198	198
COMPASS/ODOMETER	15	0	69	11	101	196	199	190
COMPASS/LASER VEL	19	0	69	12	101	202	204	203
CMPSS/U-SONIC VEL	16	0	69	11	101	194	201	200
OMEGA	27	0	54	11	101	195	197	197
LORAN	28	0	54	11	101	196	198	198
DECCA	12	0	54	11	101	179	182	181
AM-STATIONS	4	0	54	11	101	171	173	173
DIFF OMEGA	27	0	54	11	101	195	197	197
DIFF LORAN	28	0	54	11	101	196	198	198
DIFF AM-STA	5	0	54	11	101	172	174	175
RELAY OMEGA	6	0	54	11	101	173	172	176
RELAY LORAN	6	0	54	11	101	174	172	176
CLASS II								
BURIED RES LOOPS	2	168	44	297	101	612	613	610
REFLECTING SIGNS	5	77	44	54	100	289	290	287
REFLECTING ROAD	2	9	44	61	103	259	260	257
X-BAND POST	2	81	44	27	106	260	261	258
HF, VHF POST	2	9	44	15	102	172	173	171
LF POST	2	44	44	27	106	223	224	221
LIGHT/I-R POST	2	35	44	30	109	222	222	220
BURIED MAGNETS	1	17	44	45	100	203	209	206
ULTRASONIC POST	2	60	44	71	108	285	285	283
TRAFFIC SENSOR	2	67	44	39	101	253	253	251
CLASS III								
NAR-BAND FM PHASE	3	29	57	12	104	203	205	205
WID-BAND FM PHASE	30	47	69	17	203	364	367	367
PULSE T-O-ARRIVAL	26	84	139	27	179	454	456	457
NOISE CORRELATION	8	29	139	16	177	370	371	371
DIRECTION FINDER	1	79	34	15	154	282	281	281
CLASS IV								
TRAFFIC LOOPS	1	204	44	106	109	462	462	462
WAYSIDE RADIO	1	170	44	90	118	422	422	422
PHOTO/I-R DETECT	2	99	44	51	109	303	303	303
ULTRASONIC DETECT	2	103	44	51	109	307	307	307

Table 1-10. Small City
Vehicle Polling

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I TECHNIQUE	TOTAL FLEET	SINGLE SYNC	SINGLE POL	SINGLE RAND	REDUNDANT SYNC	REDUNDANT POL	REDUNDANT RAND
KEYBOARD	1 07	0 54	0 55	1 06	0 57	0 60	1 13
		0 5[illegible]	0 55	1 06	0 57	0 60	1 13
STYLUS MAP	1 12	0 56	0 57	1 09	0 62	0 65	1 17
		0 56	0 57	1 09	0 62	0 65	1 17
2-ACCELEROMETERS	1 09	0 55	0 56	1 07	0 59	0 62	1 15
		0 55	0 56	1 07	0 59	0 62	1 15
LASER VELOCIMTR	1 11	0 55	0 57	1 06	0 61	[illegible]	1 16
		0 55	0 57	1 0[illegible]	0 61	0 63	1 16
ULTRASONIC VELO	1 09	0 55	0 56	1 07	0 59	0 62	1 15
		0 55	0 56	1 07	0 59	0 62	1 15
COMPASS/ODOMETER	1 09	0 55	0 56	1 07	0 54	0 62	1 15
		0 55	0 56	1 07	0 54	0 62	1 15
COMPASS/LASER VEL	1 09	0 55	0 56	1 07	0 59	0 62	1 15
		0 55	0 56	1 07	0 59	0 62	1 15
CMPSS/U-SONIC VEL	1 09	0 55	0 56	1 07	0 59	0 62	1 15
		0 55	0 56	1 07	0 59	0 62	1 15
OMEGA	1 18	0 59	0 60	1 12	0 68	0 71	1 23
		0 59	0 60	1 12	0 68	0 71	1 23
LORAN	1 21	0 61	0 62	1 13	0 71	0 74	1 27
		0 61	0 62	1 13	0 71	0 74	1 27
DECCA	1 20	0 60	0 61	1 13	0 70	0 73	1 25
		0 60	0 61	1 13	0 70	0 73	1 25
AM-STATIONS	1 03	0 54	0 55	1 07	0 58	0 61	1 13
		0 54	0 55	1 07	0 58	0 61	1 13
DIFF OMEGA	1 18	0 59	0 60	1 12	0 68	0 71	1 23
		0 59	0 60	1 12	0 68	0 71	1 23
DIFF LORAN	1 21	0 61	0 62	1 13	0 71	0 74	1 27
		0 61	0 62	1 13	0 71	0 74	1 27
DIFF AM-STA	1 17	0 59	0 60	1 11	0 67	0 70	1 23
		0 59	0 60	1 11	0 67	0 70	1 23
RELAY OMEGA	101 40	50 50	50 51	51 03	100 50	100 53	101 05
		50 50	50 51	51 03	100 50	100 53	101 05
RELAY LORAN	4 33	2 17	2 18	2 69	3 83	3 86	[illegible] 39
		2 17	2 1[illegible]	2 69	3 [illegible]	3 86	[illegible] 39
CLASS II							
BURIED RES LOOPS	1 07	0 53	0 55	1 06	0 57	0 59	1 12
		0 53	0 55	1 06	0 57	0 59	1 12
REFLECTING SIGNS	1 07	0 53	0 55	1 06	0 57	0 59	1 12
		0 53	0 55	1 06	0 57	0 59	1 12
REFLECTING ROAD	1 07	0 53	0 55	1 06	0 57	0 59	1 12
		0 53	0 55	1 06	0 57	0 59	1 12
X-BAND POST	1 06	0 53	0 54	1 06	0 56	0 59	1 11
		0 53	0 54	1 06	0 56	0 59	1 11
HF, VHF POST	1 05	0 52	0 54	1 05	0 55	0 57	1 10
		0 52	0 54	1 05	0 55	0 57	1 10
LF POST	1 06	0 53	0 54	1 06	0 56	0 59	1 11
		0 53	0 54	1 06	0 56	0 59	1 11
LIGHT/I-R POST	1 06	0 53	0 54	1 06	0 56	0 59	1 11
		0 53	0 54	1 06	0 56	0 59	1 11
BURIED MAGNETS	1 07	0 53	0 55	1 06	0 57	0 59	1 12
		0 53	0 55	1 06	0 57	0 59	1 12
ULTRASONIC POST	1 06	0 53	0 54	1 06	0 56	0 54	1 11
		0 53	0 54	1 06	0 56	0 59	1 11
TRAFFIC SENSOR	1 06	0 53	0 54	1 06	0 56	0 54	1 11
		0 53	0 54	1 06	0 56	0 54	1 11

C. Medium Model City AVM Cost Summary Tables

Table 1-11. Medium Model City Parameters
Used in AVM Cost Analysis

AREA IS 40 SQUARE MILES.

EAST WEST DISTANCE IS 4.41 MILES.

NORTH SOUTH DISTANCE IS 8.82 MILES.

TOTAL ROAD MILEAGE IS 774 MILES.

THE NUMBER OF INTERSECTIONS IS 3500:

THE ESTIMATED NUMBER OF ROAD SEGMENTS IS 7000.

THERE ARE 100 CARS IN THE FLEET

AND THERE ARE 0 MOTORCYCLES.

THE NUMBER OF VEHICLES ON EACH SHIFT IS:

FIRST SHIFT MAX. 50

FIRST SHIFT MIN. 50

SECOND SHIFT MAX. 50

SECOND SHIFT MIN. 50

THIRD SHIFT MAX. 50

THIRD SHIFT MIN. 50

THE CITY WOULD REQUIRE 5 WIDE-BAND OR

PULSE T-O-A ANTENNA SITES AND 10 NARROW

BAND ANTENNA SITES WITH 7 AND 5 MILE COVERAGE RADII.

Table 1-12. Medium Model City AVM Cost Summary

MEDIUM MODEL CITY
CLASS I

TECHNIQUE	CARS	SITES	BASE	INST	O-M	POL	SYNC	RANDOM
		THOUSANDS OF $					TOTALS	
KEYBOARD	14	0	67	14	102	212	194	196
STYLUS MAP	255	0	67	14	100	454	430	430
2-ACCELEROMETERS	160	0	92	20	110	398	418	413
LASER VELOCIMTR	173	0	102	24	115	435	455	450
ULTRASONIC VELO	127	0	142	20	115	380	400	395
COMPASS/ODOMETER	147	0	102	12	104	331	405	395
COMPASS/LASER VEL	186	0	102	25	109	438	462	452
CMPSS/U-SONIC VEL	159	0	102	20	109	406	430	420
OMEGA	270	0	87	18	108	499	525	519
LORAN	200	0	87	15	108	509	535	531
DECCA	115	0	87	16	100	342	368	363
AM-STATIONS	40	0	87	15	106	264	283	279
DIFF OMEGA	270	0	87	18	108	499	518	519
DIFF LORAN	230	0	87	18	108	509	523	531
DIFF AM-STA	47	0	87	15	106	271	290	300
RELAY OMEGA	53	0	87	18	110	284	268	308
RELAY LORAN	58	0	87	16	110	289	273	313
CLASS II								
BURIED RES LOOPS	14	2184	67	3728	102	6110	6120	6094
REFLECTING SIGNS	48	770	67	445	172	1518	1528	1502
REFLECTING ROAD	13	84	67	520	522	1221	1231	1205
X-BAND POST	17	805	67	172	154	1230	1240	1214
HF, VHF POST	16	83	67	54	115	354	363	338
LF POST	15	408	67	172	154	862	871	846
LIGHT/I-R POST	15	350	67	210	199	849	857	832
BURIED MAGNETS	10	219	67	452	100	863	873	847
ULTRASONIC POST	14	595	67	614	173	1478	1487	1462
TRAFFIC SENSOR	15	665	67	294	101	1158	1167	1142
CLASS III								
NAR-BAND FM PHASE	23	48	127	17	108	322	347	349
WID-BAND FM PHASE	291	50	127	27	205	707	733	735
PULSE T-O-ARRIVAL	258	140	327	50	183	957	982	985
NOISE CORRELATION	79	29	327	25	179	654	663	665
DIRECTION FINDER	4	79	67	16	154	331	319	319
CLASS IV								
TRAFFIC LOOPS	8	3193	67	966	105	4424	4424	4424
WAYSIDE RADIO	8	2766	67	805	276	3921	3921	3921
PHOTO/I-R DETECT	12	1740	67	413	189	2420	2420	2420
ULTRASONIC DETECT	13	1775	67	412	189	2455	2455	2455

Table 1-13. Medium City Vehicle Polling

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I TECHNIQUE	TOTAL FLEET	SIMPLE SYNC	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	10 73	5 37	5 60	10 83	5 73	6 20	11 67
		5 37	5 60	10 83	5 73	6 20	11 67
STYLUS MAP	11 20	5 60	5 83	11 07	6 20	6 67	12 13
		5 60	5 33	11 07	6 20	6 67	12 13
2-ACCELEROMETERS	10 93	5 47	5 70	10 93	5 93	6 40	11 87
		5 47	5 70	10 93	5 93	6 40	11 87
LASER VELOCIMTR	11 07	5 53	5 77	11 00	6 07	6 53	12 00
		5 53	5 77	11 00	6 07	6 53	12 00
ULTRASONIC VELO	10 93	5 47	5 70	10 93	5 93	6 40	11 87
		5 47	5 70	10 93	5 93	6 40	11 87
COMPASS/ODOMETER	10 93	5 47	5 70	10 93	5 93	6 40	11 67
		5 47	5 70	10 93	5 93	6 40	11 87
COMPASS/LASER VEL	10 93	5 47	5 70	10 93	5 93	6 40	11 87
		5 47	5 70	10 93	5 93	6 40	11 87
CMPSS/U-SONIC VEL	10 93	5 47	5 70	10 93	5 93	6 40	11 87
		5 47	5 70	10 93	5 93	6 40	11 87
OMEGA	11 80	5 90	6 13	11 37	6 80	7 27	12 73
		5 90	6 13	11 37	6 80	7 27	12 73
LORAN	12 13	6 07	6 30	11 53	7 13	7 60	13 07
		6 07	6 30	11 53	7 13	7 60	13 07
DECCA	12 00	6 00	6 23	11 47	7 00	7 47	12 93
		6 00	6 23	11 47	7 00	7 47	12.93
AM-STATIONS	10 80	5 40	5 63	10 87	5 80	6 27	11 73
		5 40	5 63	10 87	5 80	6 27	11 73
DIFF OMEGA	11 80	5 90	6 13	11 37	6 80	7 27	12 73
		5 90	6 13	11 37	6 80	7 27	12 73
DIFF LORAN	12 13	6 07	6 30	11 53	7 13	7 60	13 07
		6 07	6 30	11 53	7 13	7 60	13 07
DIFF AM-STA	11 73	5 87	6 10	11 33	6 73	7 20	12 67
		5 87	6 10	11 33	6 73	7 20	12 67
RELAY OMEGA	1010 00	505 00	505 23	510 47	1005 00	1005 47	1010 93
		505 00	505 23	510 47	1005 00	1005 47	1010 93
RELAY LORAN	43 33	21 67	21 90	27 13	38 33	38 80	44 27
		21 67	21 90	27 13	38 33	38 80	44 27
CLASS II							
BURIED RES LOOPS	10 87	5 43	5 67	10 90	5 87	6 33	11 80
		5 43	5 67	10 90	5 87	6 33	11 80
REFLECTING SIGNS	10 87	5 43	5 67	10 90	5 87	6 33	11 80
		5 43	5 67	10 90	5 87	6 33	11 80
REFLECTING ROAD	10 87	5 43	5 67	10 90	5 87	6 33	11 80
		5 43	5 67	10 90	5 87	6 33	11 80
X-BAND POST	10 80	5 40	5 63	10 87	5 80	6 27	11 73
		5 40	5 63	10 87	5 80	6 27	11 73
HF, VHF POST	10 67	5 33	5 57	10 80	5 67	6 13	11 60
		5 33	5 57	10 80	5 67	6 13	11 60
LF POST	10 80	5 40	5 63	10 87	5 80	6 27	11 73
		5 40	5 63	10 87	5 80	6 27	11 73
LIGHT I-R POST	10 80	5 40	5 63	10 87	5 80	6 27	11 73
		5 40	5 63	10 87	5 80	6 27	11 73
BURIED MAGNETS	10 87	5 43	5 67	10 90	5 87	6 33	11 80
		5 43	5 67	10 90	5 87	6 33	11 80
ULTRASONIC POST	10 80	5 40	5 63	10 87	5 80	6 27	11 73
		5 40	5 63	10 87	5 80	6 27	11 73
TRAFFIC SENSOR	10 80	5 40	5 63	10 87	5 80	6 27	11 73
		5 40	5 63	10 87	5 80	6 27	11 73

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D. Large Model City AVM Cost Summary Tables

Table 1-14. Large Model City Parameters Used in AVM Cost Analysis

AREA IS 400 SQUARE MILES.

EAST WEST DISTANCE IS 13.9 MILES.

NORTH SOUTH DISTANCE IS 27.8 MILES.

TOTAL ROAD MILEAGE IS 7736 MILES.

THE NUMBER OF INTERSECTIONS IS 35000:

THE ESTIMATED NUMBER OF ROAD SEGMENTS IS 70000.

THERE ARE 1000 CARS IN THE FLEET

AND THERE ARE 0 MOTORCYCLES.

THE NUMBER OF VEHICLES ON EACH SHIFT IS:

FIRST SHIFT MAX. 500

FIRST SHIFT MIN. 500

SECOND SHIFT MAX. 500

SECOND SHIFT MIN. 500

THIRD SHIFT MAX. 500

THIRD SHIFT MIN. 500

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

THE CITY WOULD REQUIRE 29 WIDE-BAND OR

PULSE T-O-A ANTENNA SITES AND 106 NARROW

BAND ANTENNA SITES WITH 7 AND 3 MILE COVERAGE RADII.

Table 1-15. Large Model City AVM Cost Summary

LARGE MODEL CITY

CLASS I TECHNIQUE	CARS	SITES	BASE	INST	O-M	VOL	TOTALS SYNC	TOTALS RANDOM
	THOUSANDS OF $							
KEYBOARD	135	0	121	45	115	576	416	416
STYLUS MAP	2550	0	121	45	125	3001	2841	2841
2-ACCELEROMETERS	1600	0	161	110	200	2231	2428	2378
LASER VELOCIMTR	1780	0	161	145	250	2496	2693	2643
ULTRASONIC VELO	1270	0	161	110	250	1951	2148	2098
COMPASS/ODOMETER	1465	0	161	30	140	1956	2196	2093
COMPASS/LASER VEL	1855	0	161	160	190	2526	2766	2663
CMPSS/U-SONIC VEL	1585	0	151	110	190	2196	2436	2333
OMEGA	2700	0	141	90	175	3266	3531	3469
LORAN	2800	0	141	90	175	3366	3631	3589
DECCA	1150	0	141	70	175	1696	1961	1911
AM-STATIONS	400	0	141	60	160	921	1111	1064
DIFF. OMEGA	2700	0	141	90	175	3266	3456	3469
DIFF LORAN	2800	0	141	90	175	3366	3556	3589
DIFF AM-STA	465	0	141	60	160	986	1176	1276
RELAY OMEGA	525	0	141	90	200	1116	956	1356
RELAY LORAN	575	0	141	90	200	1166	1006	1406
CLASS II								
BURIED RES LOOPS	140	28560	121	48607	115	77703	77798	77543
REFLECTING SIGNS	480	7700	121	4360	620	13641	13736	13481
REFLECTING ROAD	125	840	121	5110	4315	10671	10766	10511
X-BAND POST	170	8050	121	1625	635	10761	10856	10601
HF, VHF POST	155	575	121	444	242	1996	2091	1836
LF POST	150	4375	121	1630	640	7076	7171	6916
LIGHT/I-R POST	145	3500	121	2010	1000	6936	7031	6776
BURIED MAGNETS	100	2656	121	5767	100	9104	9199	8944
ULTRASONIC POST	135	5950	121	6045	825	13236	13331	13076
TRAFFIC SENSOR	145	6650	121	2850	110	10036	10131	9876
CLASS III								
NAR-BAND FM PHASE	225	499	228	101	178	1231	1481	1506
WID-BAND FM PHASE	2905	336	202	144	240	3826	4086	4101
PULSE T-O-ARRIVAL	2575	1484	382	425	253	5119	5369	5394
NOISE CORRELATION	785	29	382	115	202	1672	1762	1787
DIRECTION FINDER	35	80	151	30	154	569	449	449
CLASS IV								
TRAFFIC LOOPS	80	68763	121	9567	950	79481	79481	79481
WAYSIDE RADIO	75	61233	121	7960	1860	71249	71249	71249
PHOTO\I-R DETECT	115	41140	121	4035	990	46401	46401	46401
ULTRASONIC DETECT	125	41490	121	4030	990	46756	46756	46756

Table 1-16. Large City Vehicle Polling

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I TECHNIQUE	TOTAL FLEET	SIMPLE SYNC	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	107 33	53 67	57 00	110 33	57 33	64 00	120 67
		53 67	57 00	110 33	57 33	64 00	120 67
STYLUS MAP	112 00	56 00	59 33	112 67	62 00	65 67	125 33
		56 00	59 33	112 67	62 00	65 67	125 33
2-ACCELEROMETERS	109 33	54 67	58 00	111 33	59 33	66 00	122 67
		54 67	58 00	111 33	59 33	66 00	122 67
LASER VELOCIMTR	110 67	55 33	58 67	112 00	60 67	67 33	124 00
		55 33	58 67	112 00	60 67	67 33	124 00
ULTRASONIC VELO	109 33	54 67	58 00	111 33	59 33	66 00	122 67
		54 67	58 00	111 33	59 33	66 00	122 67
COMPASS/ODOMETER	109 33	54 67	58 00	111 33	59 33	66 00	122 67
		54 67	58 00	111 33	59 33	66 00	122 67
COMPASS/LASER VEL	109 33	54 67	58 00	111 33	59 33	66 00	122 67
		54 67	58 00	111 33	59 33	66 00	122 67
CMPSS/U-SONIC VEL	109 33	54 67	58 00	111 33	59 33	66 00	122 67
		54 67	58 00	111 33	59 33	66 00	122 67
OMEGA	116 00	59 00	62 33	115 67	68 00	74 67	131 33
		59 00	62 33	115 67	68 00	74 67	131 33
LORAN	121 33	60 67	64 00	117 33	71 33	78 00	134 67
		60 67	64 00	117 33	71 33	78 00	134 67
DECCA	120 00	60 00	63 33	116 67	70 00	76 67	133 33
		60 00	63 33	116 67	70 00	76 67	133 33
AM-STATIONS	108 00	54 00	57 33	110 67	58 00	64 67	121 33
		54 00	57 33	110 67	58 00	64 67	121 33
DIFF OMEGA	116 00	59 00	62 33	115 67	68 00	74 67	131 33
		59 00	62 33	115 67	68 00	74 67	131 33
DIFF LORAN	121 33	60 67	64 00	117 33	71 33	78 00	134 67
		60 67	64 00	117 33	71 33	78 00	134 67
DIFF AM-STA	117 33	58 67	62 00	115 33	67 33	74 00	130 67
		58 67	62 00	115 33	67 33	74 00	130 67
RELAY OMEGA	10100 00	5050 00	5053 33	5106 67	10050 00	10056 67	10113 33
		5050 00	5053 33	5106 67	10050 00	10056 67	10113 33
RELAY LORAN	433 33	216 67	220 00	273 33	333 33	390 00	446 67
		216 67	220 00	273 33	333 33	390 00	446 67
CLASS II							
BURIED RES LOOPS	111 33	55 67	59 00	112 33	61 33	68 00	124 67
		55 67	59 00	112 33	61 33	68 00	124 67
REFLECTING SIGNS	111 33	55 67	59 00	112 33	61 33	68 00	124 67
		55 67	59 00	112 33	61 33	68 00	124 67
REFLECTING ROAD	111 33	55 67	59 00	112 33	61 33	68 00	124 67
		55 67	59 00	112 33	61 33	68 00	124 67
X-BAND POST	110 67	55 33	58 67	112 00	60 67	67 33	124 00
		55 33	58 67	112 00	60 67	67 33	124 00
HF, VHF POST	109 33	54 67	58 00	111 33	59 33	66 00	122 67
		54 67	58 00	111 33	59 33	66 00	122 67
LF POST	110 67	55 33	58 67	112 00	60 67	67 33	124 00
		55 33	58 67	112 00	60 67	67 33	124 00
LIGHT/I-R POST	110 67	55 33	58 67	112 00	60 67	67 33	124 00
		55 33	58 67	112 00	60 67	67 33	124 00
BURIED MAGNETS	111 33	55 67	59 00	112 33	61 33	68 00	124 67
		55 67	59 00	112 33	61 33	68 00	124 67
ULTRASONIC POST	110 67	55 33	58 67	112 00	60 67	67 33	124 00
		55 33	58 67	112 00	60 67	67 33	124 00
TRAFFIC SENSOR	110 67	55 33	58 67	112 00	60 67	67 33	124 00
		55 33	58 67	112 00	60 67	67 33	124 00

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IV. AVM SYSTEM ACCURACIES AND COST BENEFITS

A. System Parameters That Affect AVM Costs

The prediction of the expected accuracies of AVM systems is essentially a probabilistic 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-minus 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 if 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 random-walk, 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 (Sensed/Unsensed)	Mean	Variance
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 inherent 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 technique 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 mph (6.67 m/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 either is very large. The curves are shown for the system accuracy interval of 100 to 1000 meters (0.1 to 0.6 mile). The curves for less than 100 and greater than 1000 meters are repetitions of those shown and can be derived with subtraction or addition 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 is estimated by a step-by-step process. First, from the data provided for the particular city, the maximum and minimum number of vehicles deployed is obtained. Next, the number of bits in the location message required from each vehicle for each technique is determined. The time required to poll the deployed vehicles with a 0.1-sec radio turn-on time is then computed for the redundant mode of the random polling process. This value yields very conservative (or pessimistic) polling intervals 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 maximum and minimum estimation of the 95% confidence level of system accuracy for the maximum and minimum 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

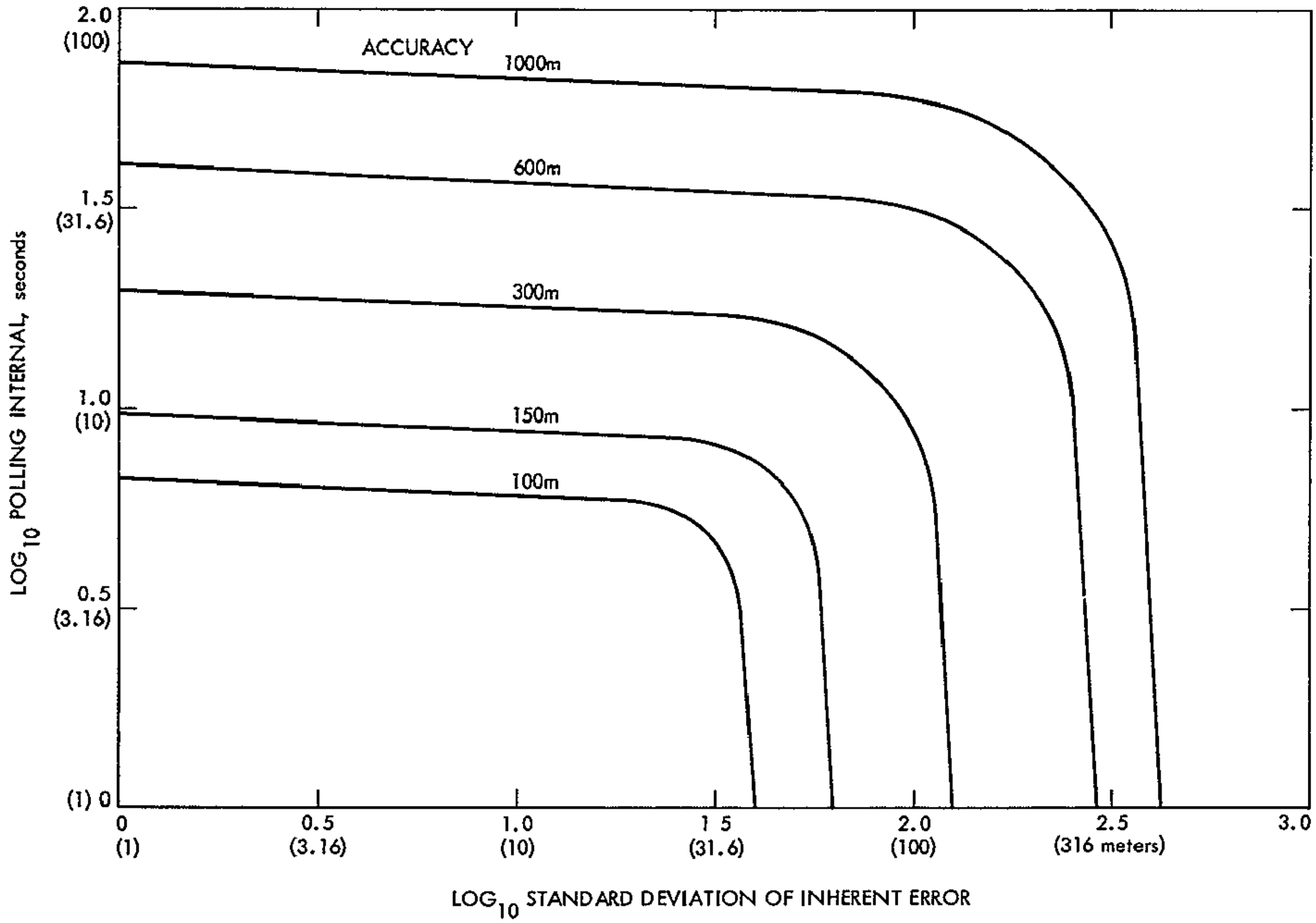

Fig. 1-36. Vehicle Polling Intervals vs 95% AVM System Accuracy

sufficient. Additionally the service improvement is found to be about 7% for the locator system dispatches versus the "center of mass" or beat vehicle 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 vehicles required to provide the same response time with no AVM. Doering's study indicated that, in the area studied (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 time 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 non-AVM 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 minimum deployments, the efficiency increase assumption yields different 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 yields no efficiency increase with maximum deployment may display a marked improvement in response. Additionally, the minimum 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 minimum deployment exceeds that for maximum deployment with a given technique.

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 minus the O-M costs of the AVM technique. The value obtained is then multiplied by 5 years for the total saving.

The 5-year saving is positive only if the value of the car saving exceeds the annual O-M cost. The calculation is performed for a given technique only if a car saving is indicated, and the result is 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 if salaries 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 1-17. Small Model City Cost Benefits from AVM System Usage

SMALL MODEL CITY
SYSTEM ACCURACIES M VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	0	36	36	0 2	0 2	-355
STYLUS MAP	30	0	75	75	0 2	0 2	-355
2-ACCELEROMETERS	34	0	39	39	0 2	0 2	-355
LASER VELOCIMTR	13	0	34	34	0 3	0 3	-235
ULTRASONIC VELO	40	0	191	191	0 2	0 2	-360
COMPASS/ODOMETER	20	0	49	49	0 2	0 2	-355
COMPASS/LASER VEL	15	0	38	38	0 3	0 3	-280
CMPSS/U-SONIC VEL	17	0	43	43	0 2	0 2	-355
OMEGA	1600	0	3693	3693	0 0	0 0	0
LORAN	160	0	370	370	0 0	0 0	0
DECCA	200	0	446	446	0 0	0 0	0
AM-STATIONS	200	0	444	444	0 0	0 0	0
DIFF OMEGA	160	0	370	370	0 0	0 0	0
DIFF LORAN	400	0	960	960	0 0	0 0	0
DIFF AM-STA	250	0	537	537	0 0	0 0	0
RELAY OMEGA	500	0	1745	1745	0 0	0 0	0
RELAY LORAN	800	0	2075	2075	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	0	27	27	0 3	0 3	-280
REFLECTING SIGNS	10	0	27	27	0 3	0 3	-315
REFLECTING ROAD	3	0	19	19	0 3	0 3	-490
X-BAND POST	12	0	32	32	0 3	0 3	-305
HF, VHF POST	15	0	38	38	0 3	0 3	-205
LF POST	170	0	241	241	0 0	0 0	0
LIGHT/I-R POST	30	0	75	75	0 2	0 2	-345
BURIED MAGNETS	4	0	17	17	0 3	0 3	-275
ULTRASONIC POST	20	0	49	49	0 2	0 2	-390
TRAFFIC SENSOR	10	0	27	27	0 3	0 3	-200
CLASS III							
NAR-BAND FM PHASE	1000	0	2331	2331	0 0	0 0	0
WID-BAND FM PHASE	1200	0	2769	2769	0 0	0 0	0
PULSE T-O-ARRIVAL	100	0	166	166	0 1	0 1	-320
NOISE CORRELATION	100	0	135	135	0 1	0 1	-810
DIRECTION FINDER	700	0	1713	1713	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	0	26	26	0 3	0 3	-320
WAYSIDE RADIO	100	0	234	234	0 0	0 0	0
PHOTO/I-R DETECT	30	0	72	72	0 2	0 2	-395
ULTRASONIC DETECT	20	0	48	48	0 2	0 2	-345

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

MEDIUM MODEL CITY
SYSTEM ACCURACIES M VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	3	199	199	1 0	1 0	210
STYLUS MAP	30	3	206	206	0 9	0 9	160
2-ACCELEROMETERS	34	3	203	203	1 0	1 0	200
LASER VELOCIMTR	13	3	199	199	1 0	1 0	175
ULTRASONIC VELO	40	2	204	204	1 0	1 0	175
COMPASS/ODOMETER	20	3	199	199	1 0	1 0	230
COMPASS/LASER VEL	15	3	198	198	1 0	1 0	205
CMPSS/U-SONIC VEL	17	3	199	199	1 0	1 0	205
OMEGA	1600	0	4077	4077	0 0	0 0	0
LORAN	160	2	408	403	0 0	0 0	0
DECCA	200	1	492	492	0 0	0 0	0
AM-STATIONS	200	1	490	490	0 0	0 0	0
DIFF OMEGA	160	2	408	403	0 0	0 0	0
DIFF LORAN	400	0	1131	1131	0 0	0 0	0
DIFF AM-STN	250	0	592	592	0 0	0 0	0
RELAY OMEGA	500	0	17459	17459	0 0	0 0	0
RELAY LORAN	300	0	2322	2322	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	3	194	194	1 1	1 1	315
REFLECTING SIGNS	10	3	194	194	1 1	1 1	-35
REFLECTING ROAD	3	3	187	187	1 2	1 2	-1710
X-BAND POST	12	3	194	194	1 1	1 1	55
HF, VHF POST	15	3	193	193	1 1	1 1	250
LF POST	190	2	270	270	0 2	0 2	-620
LIGHT/I-R POST	30	3	208	208	1 0	1 0	-200
BURIED MAGNETS	4	3	189	189	1 2	1 2	-40
ULTRASONIC POST	20	3	197	197	1 1	1 1	-48
TRAFFIC SENSOR	10	3	193	193	1 1	1 1	328
CLASS III							
NAR-BAND FM PHASE	1000	0	2607	2607	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3083	3083	0 0	0 0	0
PULSE T-O-ARRIVAL	100	2	185	185	1 2	1 2	-15
NOISE CORRELATION	100	2	207	207	0 9	0 9	-220
DIRECTION FINDER	700	0	1918	1918	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	3	23	23	3 2	3 2	1475
WAYSIDE RADIO	100	2	209	209	0 9	0 9	-705
PHOTO/I-R DETECT	30	3	61	61	2 7	2 7	1030
ULTRASONIC DETECT	20	3	43	43	2 4	2 9	1208

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

LARGE MODEL CITY
SYSTEM ACCURACIES M VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	31	2054	2057	0 0	0 0	0
STYLUS MAP	30	31	2133	2133	0 0	0 9	0
2-ACCELLROMETERS	34	31	2095	2095	0 0	0 0	0
LASER VELOCIMTR	13	33	2053	2053	0 0	0 0	0
ULTRASONIC VELO	40	30	2106	2106	0 0	0 0	0
COMPASS/ODOMETER	20	33	2062	2062	0 0	0 0	0
COMPASS/LASER VEL	15	33	2044	2044	0 0	0 0	0
CMPSS/U-SONIC VEL	17	33	2052	2052	0 0	0 0	0
OMEGA	1600	0	4080	4080	0 0	0 0	0
LORAN	160	16	2411	2411	0 0	0 0	0
DECCA	200	11	2403	2403	0 0	0 0	0
AM-STATIONS	200	11	2126	2126	0 0	0 0	0
DIFF OMEGA	160	16	2351	2351	0 0	0 0	0
DIFF LORAN	400	0	2212	2212	0 0	0 0	0
DIFF AM-STA	250	5	2371	2371	0 0	0 0	0
RELAY OMEGA	500	0	174655	174655	0 0	0 0	0
RELAY LORAN	800	0	7261	7261	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	31	2053	2053	0 0	0 0	0
REFLECTING SIGNS	10	34	2053	2053	0 0	0 0	0
REFLECTING ROAD	3	35	1930	1930	0 0	0 0	0
X-BAND POST	12	34	2053	2053	0 0	0 0	0
HF, VHF POST	15	33	2044	2044	0 0	0 0	0
LF POST	180	23	2188	2188	0 0	0 0	0
LIGHT/I-R POST	30	31	2110	2110	0 0	0 0	0
BURIED MAGNETS	4	35	1947	1997	0 0	0 0	0
ULTRASONIC POST	20	33	2035	2035	0 0	0 0	0
TRAFFIC SENSOR	10	34	2042	2042	0 0	0 0	0
CLASS III							
NAR-BAND FM PHASE	1000	0	2916	2916	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3394	3394	0 0	0 0	0
PULSE T-O-ARRIVAL	100	23	207	207	9 7	9 7	6110
NOISE CORRELATION	100	23	232	232	6 2	6 2	4090
DIRECTION FINDER	700	0	2182	2192	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	34	21	21	32 4	32 4	14550
WAYSIDE RADIO	100	23	187	187	12 2	12 2	-150
PHOTO/I-R DETECT	30	31	55	55	28 2	28 2	16200
ULTRASONIC DETECT	20	33	39	39	30 2	30 2	17700

Table 1-20. Large Model City Cost Benefits from AVM Systems Using Two RF Channels

LARGE MODEL CITYS
SYSTEM ACCURACIES M, VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	31	917	917	0 0	0 0	0
STYLUS MAP	30	31	945	945	0 0	0 0	0
2-ACCELEROMETERS	34	31	931	931	0 0	0 0	0
LASER VELOCIMTR	13	33	917	917	0 0	0 0	0
ULTRASONIC VELO	40	30	935	935	0 0	0 0	0
COMPASS/ODOMETER	20	33	918	918	0 0	0 0	0
COMPASS/LASER VEL	15	33	912	912	0 0	0 0	0
CMPSS/U-SONIC VEL	17	33	915	915	0 0	0 0	0
OMEGA	1600	0	3966	3966	0 0	0 0	0
LORAN	160	16	1194	1194	0 0	0 0	0
DECCA	200	11	1190	1190	0 0	0 0	0
AM-STATIONS	200	11	965	965	0 0	0 0	0
DIFF OMEGA	160	16	1163	1163	0 0	0 0	0
DIFF LORAN	400	0	1144	1144	0 0	0 0	0
DIFF AM-STN	250	5	1173	1173	0 0	0 0	0
RELAY OMEGA	500	0	79750	79750	0 0	0 0	0
RELAY LORAN	800	0	3857	3857	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	34	915	915	0 0	0 0	0
REFLECTING SIGNS	10	34	915	915	0 0	0 0	0
REFLECTING ROAD	3	35	887	887	0 0	0 0	0
X-BAND POST	12	34	915	915	0 0	0 0	0
HF, VHF POST	15	33	912	912	0 0	0 0	0
LF POST	100	23	966	966	0 0	0 0	0
LIGHT/I-R POST	30	31	937	937	0 0	0 0	0
BURIED MAGNETS	4	35	894	894	0 0	0 0	0
ULTRASONIC POST	20	33	927	927	0 0	0 0	0
TRAFFIC SENSOR	10	34	911	911	0 0	0 0	0
CLASS III							
NAR-BAND FM PHASE	1000	0	2819	2819	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3297	3297	0 0	0 0	0
PULSE T-O-ARRIVAL	100	23	207	207	9 7	9 7	6810
NOISE CORRELATION	100	23	232	232	6 8	6 8	4040
DIRECTION FINDER	700	0	1355	1055	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	34	21	21	32 4	32 4	19550
WAYSIDE RADIO	100	23	187	187	12 2	12 2	-150
PHOTO/I-R DETECT	30	31	55	55	28 2	23 2	16200
ULTRASONIC DETECT	20	33	39	39	30 2	30 2	17700

V. COMPUTER PROGRAMS 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 generally 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 city 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 individual 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 readily available in real cities. It can be made easily 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 simulation 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 Synthesis 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 life-cost equations. A preliminary concept of the basic elements of the AVM system synthesis computer program is 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 with 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 will supply the values of those parameters that describe his particular city. Some of the data may be fairly extensive, for example, geocoding data or DIME file type information which describes the city street/block system in detail. For information of this type a computer-readable data file 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 data file and determine the AVM system configurations suited to the city. If any data is missing or incomplete, the program will indicate 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 configuration option.

Step 4. After selecting the viable configuration options, the program will shift to a "trade-off" or compromise mode in which the user can access further detail and investigate the options available within 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: XX.XX mi. 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
Shift hours: HH-HH, HH-HH, HH-HH
Number of dispatcher consoles: N
Utilization factor by shift: FF%, FF%, FF% (This is 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: P%, P%, P%
RF channel assigned· N Planned: N
LORAN coverage in area ?: Y-N; DECCA ?: Y-N
AM stations in area K--, W--, K--, W--

2. AVM Configuration options for AVM System Synthesis. Each of the AVM options identified by the selection process will be described briefly in narrative form. Each will be tagged with an identity 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

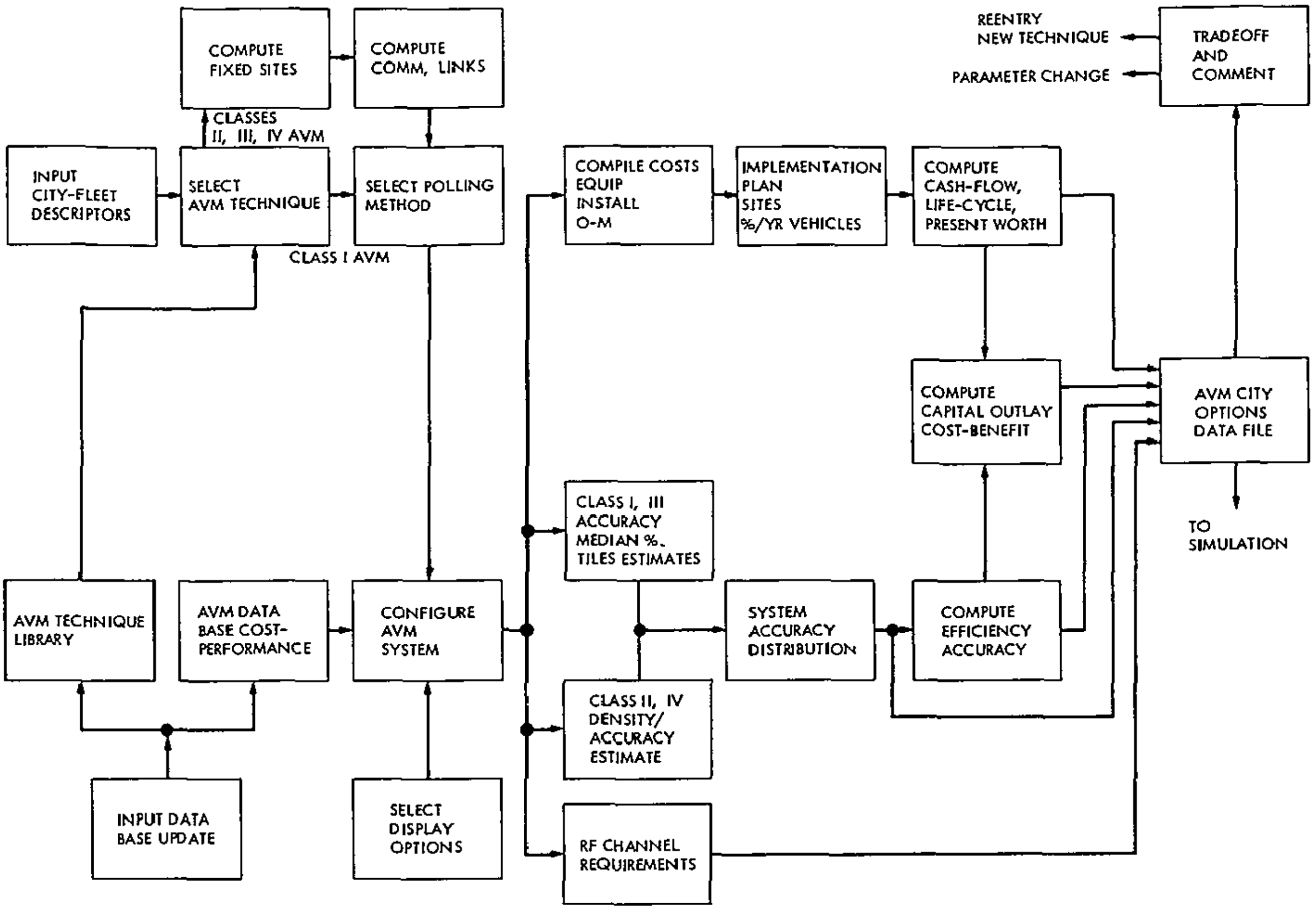

Figure 1-37. Concept for AVM System Synthesis Computer Program

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
$XXX XXX plus $XX XXX per year (each)
Fixed sites
$XXX XXX plus $XX XXX per year (each)
Signposts
$ XXX plus $ XXX per year (each)
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 = XX vehicles/ second)

Fraction of fleet with error

less than_____ft: XX%

less than_____ft: XX%

less than_____ft: XX%

d. Comments. Design features and other relevant considerations will be noted. Typical comments that might apply to specific systems are as follows:

"Vehicle status is monitored".

"Field unit alarm capability is present".

"Polling procedures are inflexible".

"Shared usage by several agencies would be difficult to implement".

"Effect of weather on performance expected to be small".

"Fleet locations easily monitored by public".

"Each 90 vehicles monitored requires an additional radio channel".

"Sensors may require protection from vandalism".

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 estimate. A preliminary estimate 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:
  $XX, XXX per year
Patrolmen required for each vehicle: N
Support personnel for each vehicle: N.N
Overhead on salaries: PP%
Replacement cost of vehicle: $X, XXX
Maintenance cost of vehicle:
  $X, XXX per year

Based on the size of the fleet and these parameters, a cost benefit (deficit) first estimate will be provided such as:

Number of vehicles saved by shift. X, X, X
Vehicle cost saving equivalent: $XXX, XXX
AVM capital investment equivalent,
  10 yr: $XXX, XXX
  5 yr: $XXX, 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 techniques 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 is 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 entire 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 percentile 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 either X and Y or with an angle and range to the exact location. The apparent location is then used by the dispatching routine 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 intervals between vehicle location determinations. Short interval interrogation of location is not a requisite mode of operation in many AVM techniques and is impractical or inappropriate in others.

A more realistic approach to AVM accuracy simulation is to model the actual vehicle location process, including the expected or appropriate polling technique and taking into consideration the time lapse from the last location determination, the motion of the vehicles, and the resultant effect on closest car determination. In this mode of simulation, 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 differences in X- and Y-distances from the vehicle position to the location of the call for assistance give a correct solution only for idealized 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 appraisal of the expected increase in efficiency can be determined. In addition, the possible variations in system configuration that affect performance parameters of the entire system can be investigated with the assurance that the influence of the variation has been considered.

Other technical 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 indicated, the intent is 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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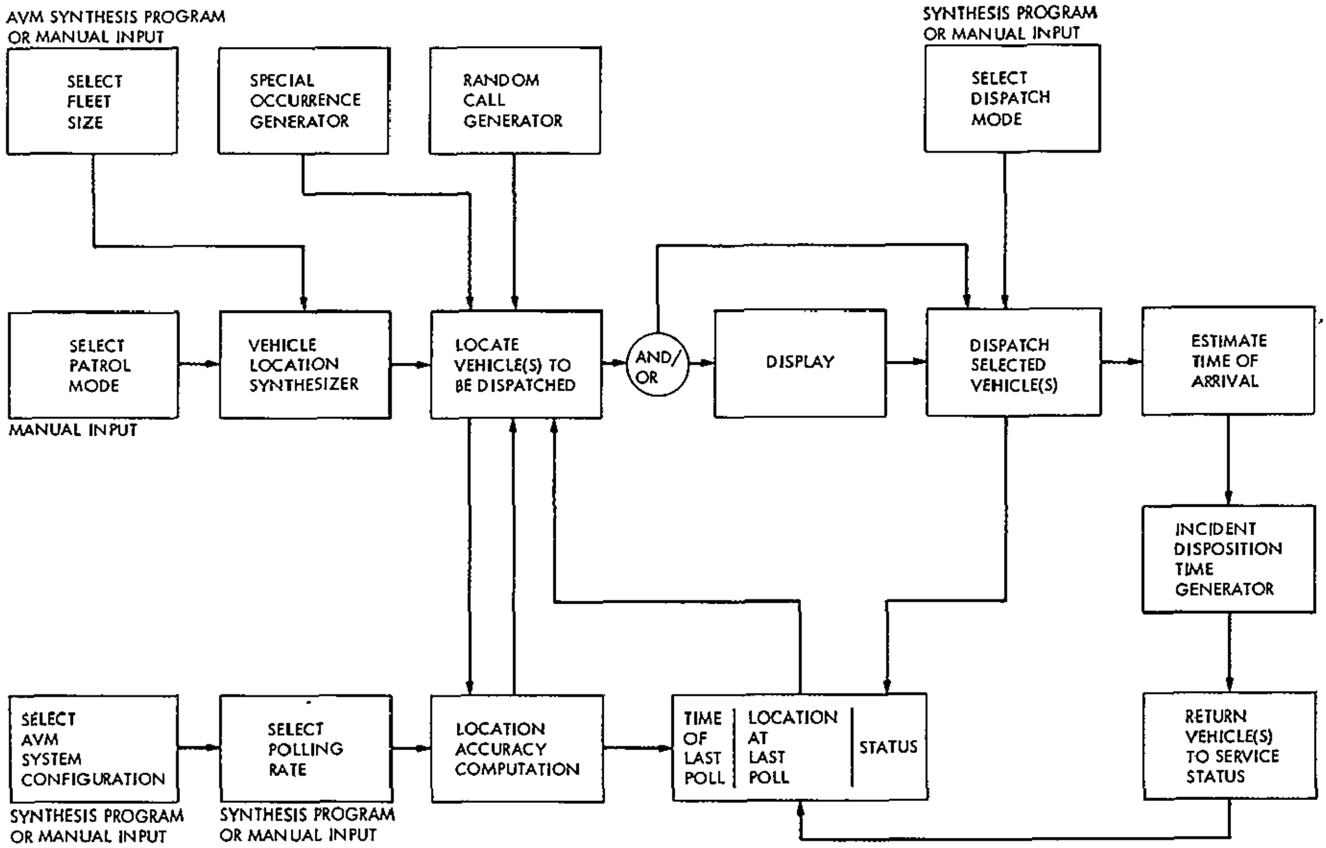

Figure 1-38. Concept for AVM System Simulation Computer Program

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PART TWO: AVM DATA FOR USER GROUP ADVISORY COMMITTEE CITIES

G.R. Hansen

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FIGURES

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I. COST BENEFITS OF AVM SYSTEMS FOR SEVEN CITIES

A. Rationale for Selection of UGAC Cities

In order that a more realistic appraisal of the costs and expected performance of AVM Systems could be estimated, police department representatives from several cities 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 California cities for the UGAC study. Some criteria are obvious and were established for time and economic considerations, while others were arrived at by heuristic processes. In this listing, the future tense is used because the criteria were established before city 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 desirable 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 cities. This criterion will eliminate those cities formed to be wholly agricultural or industrial areas for tax purposes.

(4) Building Sizes. The inclusion of high-rise dense metropolitan, low-rise business (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 arbitrary 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 will probably have different authority within their city governments as a function of population. It is believed, that those from smaller cities may be closer to the policy making level than those from major cities.

(6) Willingness to Cooperate. This is an obvious but important criterion and is difficult to assess beforehand. It is 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 available 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 requirement, but is necessary to eliminate those cities that contract for police services with another government agency. These cities would probably fail Criterion (7) as well. This criterion is a natural outgrowth of the principal thrust of the proposed work which will focus on public safety vehicle location.

None of the foregoing criteria were intended to preclude participation by governmental bodies other than cities, such as counties. By criterion (8), only Los Angeles and possibly, 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. Medium cities selected were Pasadena, Long Beach, and Anaheim. 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 officers 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 (i.e., pastels) in response to citizen calls. The inclusion of motorcycles, either 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 vehicles in the fleet. The total number of vehicles to be instrumented is the basis for the car cost estimates. 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-shift operation. This parameter is necessary to determine vehicle 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 response-time 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 technique 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 narrow-band 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 cities 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) Minimum 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 compiled 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 estimations.

C. Descriptions and Summary Analyses of UGAC Cities

In Sections II through VIII, outline maps of each UGAC city are presented along with detailed 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 cities 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 accuracies were determined for shorter cycle times or polling intervals. That is, more than one RF channel (half-duplex) was allowed for these areas.

In this Section, the summary analyses for each UGAC city 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 magnetic-compass/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 Anaheim 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 dead-reckoning 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 $144/km^2$ (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. Wide-spaced 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 dead-reckoning 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 wide-spaced signpost 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 (O-M) personnel indicated as required for all systems.

The system accuracy indicated for the wide-spaced 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 mile) with slightly fewer signposts. The system costs are quite similar for the technique if the O-M category is omitted ($60K versus $71K). (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 city, 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 is roughly half-way between the small and medium models. Again a car saving is 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 against 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, virtually 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 despite 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 were uniformly increased by about $1.8 million 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 km^2 (50 to 200 square miles). Again as in the medium model city, all of the bureaus show a 5-year saving for most of the AVM techniques. 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 twice 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 O-M expenses (See Sect. VIII.)

II. Anaheim, CA, City AVM Cost Benefit Analysis Tables

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

```
AREA IS 53.5 SQUARE MILES.

EAST WEST DISTANCE IS 15.3 MILES.

NORTH SOUTH DISTANCE IS 6 MILES

TOTAL ROAD MILEAGE IS 456 MILES.

THE NUMBER OF INTERSECTIONS IS 4300.

THE ESTIMATED NUMBER OF ROAD SEGMENTS IS 4600

THERE ARE 56 CARS IN THE FLEET.

AND THERE ARE 0 MOTORCYCLES.

THE NUMBER OF VEHICLES ON EACH SHIFT IS:

FIRST SHIFT MAX. 14

FIRST SHIFT MIN. 14

SECOND SHIFT MAX. 12

SECOND SHIFT MIN. 12

THIRD SHIFT MAX. 19

THIRD SHIFT MIN. 19

THE NUMBER OF DISPATCHERS IS 1

THE CITY WOULD REQUIRE 6 WIDE-BAND OR
PULSE ANTENNA SITES AND 16 NARROW BAND
FM ANTENNA SITES FOR 7 AND 3 MILE RADIUS COVERAGE.
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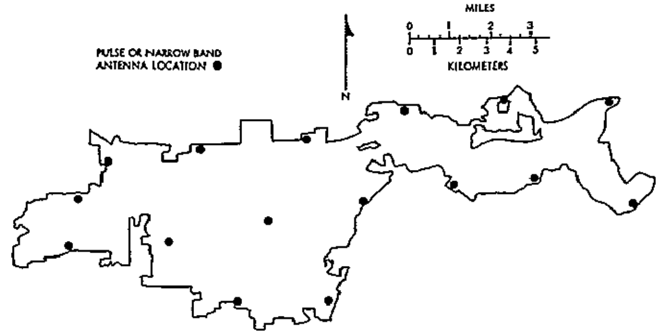

Figure 2-1. Anaheim, CA, AVM Pulse or Narrow-Band Antenna Locations

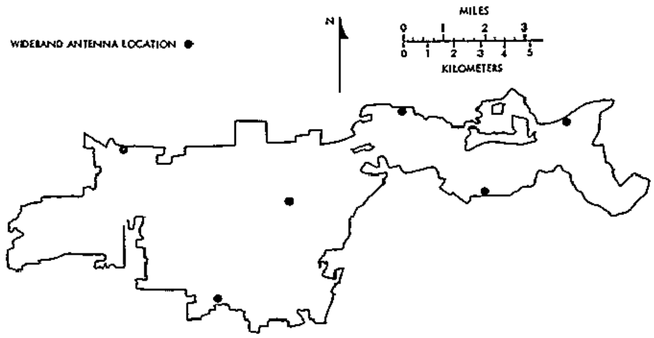

Figure 2-2. Anaheim, CA, AVM Wide-Band Antenna Locations

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

ANAHEIM

CLASS I		THOUSANDS OF $					TOTALS	
TECHNIQUE	CARS	SITES	BASE	INST	O-M	VOL	SYNC	RANDOM
KEYBOARD	5	0	59	12	101	1 2	176	176
STYLUS MAP	92	0	59	12	101	269	263	263
2-ACCELEROMETERS	56	0	80	14	104	261	268	266
LASER VELOCIMTR	65	0	90	15	106	281	289	286
ULTRASONIC VELO	46	0	90	14	106	261	268	266
COMPASS/ODOMETER	53	0	90	11	102	261	270	266
COMPASS/LASER VEL	67	0	90	16	104	282	290	287
CMPSS/U-SONIC VEL	58	0	90	14	104	270	279	275
OMEGA	38	0	75	13	103	294	304	301
LORAN	101	0	75	13	103	298	307	306
DECCA	42	0	75	13	103	233	247	245
AM-STATIONS	15	0	75	12	103	210	216	215
DIFF OMEGA	48	0	75	13	103	294	301	301
DIFF LORAN	101	0	75	13	103	293	304	306
DIFF AM-STA	17	0	75	12	103	212	219	222
RELAY OMEGA	14	0	75	13	104	217	211	225
RELAY LORAN	21	0	75	13	104	218	213	227
CLASS II								
BURIED RES LOOPS	6	3226	59	5496	101	8892	8895	8886
REFLECTING SIGNS	18	1056	59	592	197	1927	1930	1921
REFLECTING ROAD	5	116	59	704	677	1565	1568	1559
X-BAND POST	7	1104	59	228	173	1575	1579	1569
HF VHF POST	6	120	59	66	114	375	378	369
LF POST	6	600	54	228	173	1071	1074	1065
LIGHT/I-R POST	6	460	59	277	221	1048	1051	1042
BURIED MAGNETS	4	323	59	657	100	1148	1152	1142
ULTRASONIC POST	5	816	59	830	197	1912	1915	1906
TRAFFIC SENSOR	6	912	59	396	101	1478	1482	1473
CLASS III								
NAR-BAND FM PHASE	9	76	103	18	109	313	322	323
WID-BAND FM PHASE	105	70	110	23	204	511	520	521
PULSE T-O-ARRIVAL	93	224	257	56	194	313	322	323
NOISE CORRELATION	29	29	257	14	178	516	519	520
DIRECTION FINDER	2	73	57	16	154	310	306	306
CLASS IV								
TRAFFIC LOOPS	3	2343	53	1315	216	4535	4535	4535
WAYSIDE RADIO	3	2476	59	1097	341	3974	3974	3974
PHOTO/I-R DETECT	5	1455	59	555	221	2293	2293	2293
ULTRASONIC DETECT	5	1503	59	555	221	2342	2342	2342

Table 2-3. Anaheim, CA, AVM Polling Cycle Min/Max Times

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I TECHNIQUE	TOTAL FLEET	SIMPLE SYNC	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	3 86	2 04	2 12	4 09	2 18	2 33	4 38
		1 29	1 34	2 53	1 38	1 47	2 77
STYLUS MAP	4 03	2 13	2 20	4 18	2 36	2 51	4 56
		1 34	1 39	2 64	1 49	1 58	2 88
2-ACCELEROMETERS	3 94	2 08	2 15	4 13	2 25	2 41	4 46
		1 31	1 36	2 61	1 42	1 52	2 82
LASER VELOCIMTR	3 98	2 10	2 18	4 16	2 31	2 46	4 51
		1-33	1 38	2 62	1 46	1 55	2 85
ULTRASONIC VELO	3 94	2 08	2 15	4 13	2 25	2 41	4 46
		1 31	1 36	2 61	1 42	1 52	2 82
COMPASS/ODOMETER	3 94	2 08	2 15	4 13	2 25	2 41	4 46
		1 31	1 36	2 61	1 42	1 52	2 82
COMPASS/LASER VEL	3 94	2 08	2 15	4 13	2 25	2 41	4 46
		1 31	1 36	2 61	1 42	1 52	2 82
CMPSS/U-SONIC VEL	3 94	2 08	2 15	4 13	2 25	2 41	4 46
		1 31	1 36	2 61	1 42	1 52	2 82
OMEGA	4 25	2 24	2 32	4 29	2 58	2 74	4 79
		1 42	1 46	2 71	1 63	1 73	3 02
LORAN	4 37	2 31	2 38	4.36	2 71	2 86	4 92
		1 46	1 50	2 75	1 71	1 81	3 10
DECCA	4 32	2 28	2 36	4 33	2 66	2 81	4 86
		1 44	1 49	2 74	1 68	1 78	3 07
AM-STATIONS	3 89	2 05	2 13	4 10	2 20	2 36	4 41
		1 30	1 34	2 59	1 39	1 49	2 78
DIFF OMEGA	4 25	2 24	2 32	4 29	2 58	2 74	4 79
		1 42	1 46	2 71	1 63	1 73	3 02
DIFF LORAN	4 37	2 31	2 38	4 36	2 71	2 86	4 92
		1 46	1 50	2 75	1 71	1 81	3 10
DIFF AM-STA	4 22	2 23	2 31	4 28	2 56	2 71	4 76
		1 41	1 46	2 70	1 62	1 71	3 01
RELAY OMEGA	363 60	191 90	191 98	193 95	381 90	382 05	384 10
		121 20	121 25	122 50	241 20	241 30	242-59
RELAY LORAN	15 60	8 23	8 31	10 29	14 57	14 72	16 77
		5 20	5 25	6 50	9 20	9 30	10 59
CLASS II							
BURIED RES LOOPS	3 94	2 08	2 15	4 13	2 25	2 41	4 46
		1 31	1 36	2 61	1 42	1 52	2 82
REFLECTING SIGNS	3 94	2-08	2 15	4 13	2 25	2 41	4 46
		1 31	1 36	2 61	1 42	1 52	2 82
REFLECTING ROAD	3 94	2 08	2 15	4 13	2 25	2 41	4 46
		1 31	1 36	2 61	1 42	1 52	2 82
X-BAND POST	3 91	2 06	2 14	4 12	2 23	2 38	4 43
		1 30	1 35	2 60	1-41	1 50	2 80
HF, VHF POST	3 86	2 04	2 12	4 09	2 18	2 33	4 38
		1 29	1 34	2 58	1 38	1 47	2 77
LF POST	3 91	2 06	2 14	4 12	2 23	2 38	4 43
		1 30	1 35	2 60	1 41	1 50	2 80
LIGHT/I-R POST	3 91	2 06	2 14	4 12	2 23	2 38	4 43
		1 30	1 35	2 60	1 41	1 50	2 80
BURIED MAGNETS	3 94	2 08	2 15	4 13	2 25	2 41	4 46
		1 31	1 36	2 61	1 42	1 52	2 82
ULTRASONIC POST	3 91	2 06	2 14	4 12	2 23	2 38	4 43
		1-30	1 35	2 60	1 41	1 50	2 80
TRAFFIC SENSOR	3 91	2-06	2 14	4 12	2 23	2 38	4 43
		1 30	1 35	2 60	1 41	1 50	2 80

Table 2-4. Anaheim, CA, AVM Accuracies and Cost Benefits

ANAHEIM

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	50	1	44	41	0 7	1 0	245
STYLUS MAP	50	1	83	38	0 7	1 0	245
2-ACCELEROMETERS	54	1	43	95	0 7	1 0	230
LASER VELOCIMTR	13	1	74	49	0 7	1 1	295
ULTRASONIC VELO	41	1	108	105	0 6	1 0	220
COMPASS/ODOMETER	20	1	74	51	0 7	1 1	315
COMPASS/LASER VEL	15	1	74	49	0 7	1 1	305
CMPSS/U-SONIC VEL	17	1	74	49	0 7	1 1	305
OMEGA	1600	0	3914	3640	0 0	0 0	0
LORAN	160	1	392	381	0 2	0 1	-365
DECCA	200	1	472	463	0 1	0 0	-440
AM-STATIONS	200	1	470	461	0 1	0 0	-440
DIFF OMEGA	160	1	391	384	0 2	0 1	-365
DIFF LORAN	400	0	1081	1054	0 0	0 0	0
DIFF AM-STA	250	1	563	550	0 0	0 0	0
RELAY OMEGA	500	0	6307	4115	0 0	0 0	0
RELAY LORAN	300	0	2215	2166	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	1	73	43	0 7	1 1	320
REFLECTING SIGNS	10	1	73	43	0 7	1 1	-160
REFLECTING ROAD	3	1	71	47	0 7	1 1	-2510
X-BAND POST	12	1	73	48	0 7	1 1	-40
HF, VHF POST	15	1	73	43	0 7	1 1	230
LF POST	100	1	258	252	0 4	0 5	-490
LIGHT/I-R POST	30	1	62	30	0 7	1 0	-355
BURIED MAGNETS	4	1	71	47	0 7	1 1	325
ULTRASONIC POST	20	1	74	51	0 7	1 1	-160
TRAFFIC SENSOR	10	1	73	43	0 7	1 1	320
CLASS III							
NAR-BAND FM PHASE	1000	0	2488	2433	0 0	0 0	0
WID-BAND FM PHASE	1200	0	2954	2889	0 0	0 0	0
PULSE T-O-ARRIVAL	100	1	177	173	0 5	0 9	-320
NOISE CORRELATION	100	1	196	194	0 5	0 7	-365
DIRECTION FINDER	700	0	1830	1730	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	1	25	25	0 5	1 2	-150
WAYSIDE RADIO	100	1	219	224	0 5	0 6	-1255
PHOTO-I-R DETECT	30	1	65	63	0 7	1 1	-230
ULTRASONIC DETECT	20	1	45	46	0 7	1 1	-280

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

Table 2-5. Long Beach, CA, City AVM Physical Parameters

AREA IS 50.2 SQUARE MILES.

EAST WEST DISTANCE IS 10 MILES.

NORTH SOUTH DISTANCE IS 9.6 MILES.

TOTAL ROAD MILEAGE IS 2000 MILES.

THE NUMBER OF INTERSECTIONS IS 5000.

THE ESTIMATED NUMBER OF ROAD SEGMENTS IS 10000:

THERE ARE 61 CARS IN THE FLEET.

AND THERE ARE 51 MOTORCYCLES.

THE NUMBER OF VEHICLES ON EACH SHIFT IS:

FIRST SHIFT MAX 16

FIRST SHIFT MIN. 16

SECOND SHIFT MAX 16

SECOND SHIFT MIN. 16

THIRD SHIFT MAX. 16

THIRD SHIFT MIN. 16

THE NUMBER OF DISPATCHERS IS 2

THE CITY WOULD REQUIRE 7 WIDE-BAND OR

PULSE ANTENNA SITES AND 21 NARROW BAND

FM ANTENNA SITES FOR 7 AND 3 MILE RADIUS COVERAGE

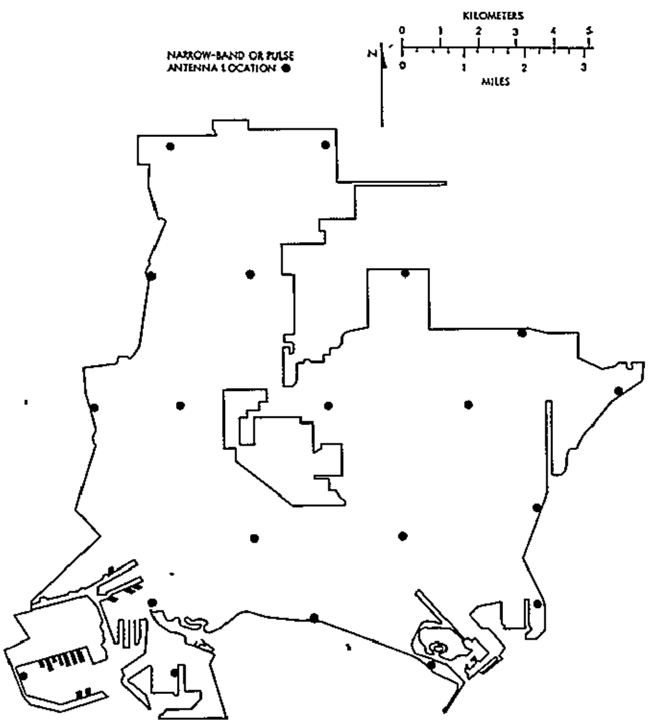

Figure 2-3. Long Beach, CA, AVM Pulse or Narrow-Band Antenna Locations

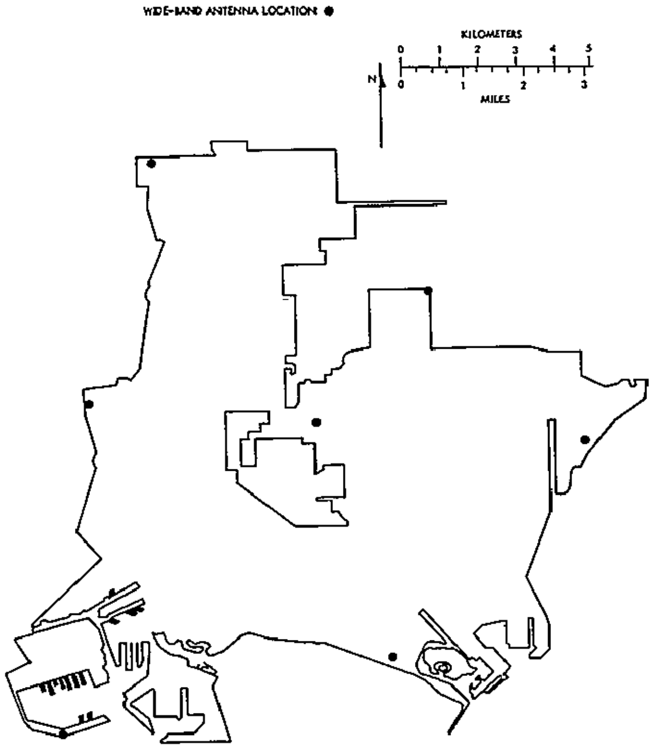

Figure 2-4. Long Beach, CA, AVM Wide-Band Antenna Locations

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

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I TECHNIQUE	TOTAL FLEET	SIMPLE SYNC	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	12 82	1 72	1 79	3 47	1 83	1 98	3 73
		1 72	1 79	3 47	1 83	1 98	3 73
STYLUS MAP	12 54	1 79	1 87	3 54	1 98	2 13	3 88
		1 79	1 87	3 54	1 98	2 13	3 88
2-ACCELEROMETERS	12 25	1 75	1 82	3 58	1 90	2 05	3 80
		1 75	1 82	3 58	1 90	2 05	3 80
LASER VELOCIMTR	12.40	1 77	1 85	3 52	1 94	2 09	3 84
		1 77	1 85	3 52	1 94	2 09	3 84
ULTRASONIC VELO	12.25	1 75	1 82	3 58	1 90	2 05	3 80
		1 75	1 82	3 58	1 90	2 05	3 80
COMPASS/ODOMETER	12.25	1 75	1 82	3 58	1 90	2 05	3 80
		1 75	1 82	3 58	1 90	2 05	3 80
COMPASS/LASER VEL	12.25	1.75	1 82	3 58	1.90	2 05	3 80
		1 75	1 82	3 58	1 90	2 05	3 80
CMPSS/U-SONIC VEL	12.25	1 75	1 82	3 58	1 90	2 05	3 80
		1 75	1 82	3 58	1 90	2 05	3 80
OMEGA	13 22	1 89	1 96	3 64	2 18	2 33	4 07
		1 89	1 96	3.64	2.18	2.33	4 07
LORAN	13 59	1.94	2 02	3 69	2.28	2.43	4.18
		1 94	2 02	3 69	2 28	2 43	4 18
DECCA	13 44	1.92	1.99	3 67	2 24	2.39	4 14
		1.92	1 99	3 67	2.24	2.39	4 14
AM-STATIONS	12 10	1 73	1 80	3 48	1.86	2 01	3 75
		1.73	1 80	3 48	1.86	2.01	3 75
DIFF OMEGA	13 22	1.89	1 96	3.64	2.18	2.33	4 07
		1 89	1 96	3.64	2 18	2 33	4 07
DIFF. LORAN	13 59	1.94	2.02	3 69	2 28	2 43	4 18
		1.94	2.02	3 69	2.28	2.43	4 18
DIFF AM-STA	13 14	1 88	1 95	3 63	2 16	2 30	4 05
		1.88	1 95	3 63	2 16	2.30	4 05
RELAY OMEGA	1131.20	161.68	161.68	163 35	321 60	321 75	323 50
		161 68	161 68	163 35	321 60	321.75	323 50
RELAY LORAN	48 53	6 93	7 01	8 68	12 27	12 42	14 17
		6 93	7 01	8 68	12 27	12 42	14 17
CLASS II							
BURIED RES LOOPS	12 25	1.75	1.82	3 58	1 90	2.05	3 80
		1.75	1 82	3 58	1 90	2 05	3 80
REFLECTING SIGNS	12 25	1 75	1 82	3 58	1 90	2 05	3 80
		1.75	1 82	3 58	1 90	2 05	3 80
REFLECTING ROAD	12 25	1.75	1.82	3 58	1 90	2 05	3 80
		1 75	1.82	3 58	1 90	2 05	3 80
X-BAND POST	12 17	1.74	1.81	3 49	1 88	2 03	3 78
		1 74	1.81	3 49	1 88	2 03	3 78
HF, VHF POST	12 82	1 72	1.79	3 47	1 83	1 98	3 73
		1.72	1.79	3 47	1 83	1.98	3 73
LF POST	12 17	1.74	1.81	3 49	1 88	2 03	3 78
		1 74	1.81	3 49	1 88	2 03	3 78
LIGHT/I-R POST	12 17	1 74	1.81	3 49	1 88	2 03	3 78
		1 74	1.81	3 49	1 88	2 03	3 78
BURIED MAGNETS	12 25	1 75	1.82	3 58	1 90	2 05	3 80
		1 75	1.82	3 58	1 90	2 05	3 80
ULTRASONIC POST	12 17	1 74	1.81	3 49	1 88	2 03	3 78
		1 74	1 81	3 49	1 88	2 03	3 78
TRAFFIC SENSOR	12 17	1 74	1.81	3 49	1 88	2 03	3 78
		1.74	1 81	3 49	1 88	2 03	3 78

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

LONG BEACH
CLASS I

THOUSANDS OF $

TECHNIQUE	CAPS	SITES	BASE	INST	O-M	VOL	SYNC	RANDOM
KEYBOARD	3	0	66	13	101	198	166	109
STYLUS MAP	156	0	66	13	102	345	336	336
2-ACCELEROMETERS	90	0	90	17	107	320	332	329
LASER VELOCIMTR	109	0	99	19	110	345	357	354
ULTRASONIC VELO	78	0	99	17	110	312	324	321
COMPASS/ODOMETER	90	0	99	12	100	312	327	321
COMPASS/LASER VEL	114	0	99	20	106	347	362	355
CMPSS/U-SONIC VEL	97	0	38	17	106	327	341	335
OMEGA	165	0	84	15	105	376	345	391
LORAN	171	0	84	15	105	385	401	398
DECCA	71	0	34	14	105	200	244	296
AM-STATIONS	25	0	84	14	104	235	247	244
DIFF OMEGA	165	0	84	15	105	378	340	391
DIFF LORAN	171	0	84	15	105	385	396	393
DIFF AM-STA	29	0	84	14	104	239	251	257
RELAY OMEGA	33	0	84	15	107	247	230	262
RELAY LORAN	36	0	84	15	107	250	241	265
CLASS II								
BURIED RES LOOPS	9	3360	66	5725	107	9270	9276	9261
REFLECTING SIGNS	10	1100	66	620	202	2026	2032	2016
REFLECTING ROAD	8	120	66	734	701	1638	1644	1629
X-BAND POST	11	1640	66	373	221	2520	2525	2510
HF, VHF POST	19	200	66	103	131	514	525	509
LF POST	10	1000	66	373	221	1673	1635	1669
LIGHT/I-R POST	9	840	66	455	302	1641	1647	1631
BURIED MAGNETS	7	336	66	635	100	1203	1209	1193
ULTRASONIC POST	9	350	66	366	202	2001	2007	1991
TRAFFIC SENSOR	9	950	66	413	101	1540	1554	1538
CLASS III								
NAR-BAND FM PHASE	14	44	119	21	113	365	3 0	362
WID-BAND FM PHASE	178	61	126	26	206	616	630	632
PULSE T-O-ARRIVAL	153	294	298	72	108	1103	1023	1025
NOISE CORRELATION	43	29	299	21	179	533	589	590
DIRECTION FINDER	3	79	67	16	154	325	317	317
CLASS IV								
TRAFFIC LOOPS	5	16160	66	2194	293	18735	13735	18735
WAYSIDE RADIO	5	10946	66	1143	351	12510	12510	12510
PHOTO\I-R DETECT	3	9708	66	919	301	11000	11000	11000
ULTRASONIC DETECT	6	9788	66	918	301	11080	11080	11080

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

LONG BEACH

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	1	43	93	0 9	0 9	170
STYLUS MAP	30	1	32	32	0 9	0 9	165
2-ACCELEROMETERS	34	1	47	47	0 9	0 9	140
LASER VELOCIMTR	13	1	65	65	0 9	0.9	125
ULTRASONIC VELO	40	1	107	107	0 9	0 9	125
COMPASS/ODOMETER	20	1	65	65	0 9	0 9	160
COMPASS/LASER VEL	15	1	64	64	0 9	0 9	145
CMPSS/U-SONIC VEL	17	1	64	64	0 9	0 9	145
OMEGA	1500	0	3380	3380	0 0	0 0	0
LORAN	160	1	369	389	0 3	0 3	-300
DECCA	200	1	469	469	0 1	0 1	-450
AM-STATIONS	200	1	467	467	0 2	0 2	-370
DIFF OMEGA	160	1	339	309	0 3	0 3	-340
DIFF LORAN	400	0	1073	1073	0 0	0 0	0
DIFF AM-STA	250	1	565	565	0 0	0 0	0
RELAY OMEGA	300	0	5394	5394	0 0	0 0	0
RELAY LORAN	300	0	2197	2197	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	1	64	64	0 4	0 4	-170
REFLECTING SIGNS	10	1	64	64	0 9	0 9	-365
REFLECTING ROAD	3	1	62	62	0 9	0 9	-2030
X-BAND POST	12	1	64	64	0 9	0 9	-400
HF, VHF POST	15	1	63	63	0 4	0 4	20
LF POST	100	1	256	256	0 6	0 6	-655
LIGHT/I-R POST	30	1	22	22	0 9	0 9	-665
BURIED MAGNETS	4	1	62	62	0 9	0 4	-175
ULTRASONIC POST	20	1	64	64	0 9	0 4	-755
TRAFFIC SENSOR	10	1	60	60	0 9	0 4	170
CLASS III							
NAR-BAND FM PHASE	1000	0	2467	2467	0 0	0 0	0
WID-BAND FM PHASE	1200	0	2930	2930	0 0	0 0	0
PULSE T-O-ARRIVAL	100	1	175	175	0 7	0 7	-415
NOISE CORRELATION	100	1	196	196	0 7	0 7	-370
DIRECTION FINDER	700	0	1815	1815	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	1	25	25	1 0	1 0	-7715
WAYSIDE RADIO	100	1	221	221	0 6	0 6	-1305
PHOTO\I-R DETECT	30	1	66	66	0 9	0 9	-630
ULTRASONIC DETECT	20	1	45	45	1 0	1 0	-755

IV. Montclair, CA, City AVM Cost Benefit Analysis Tables

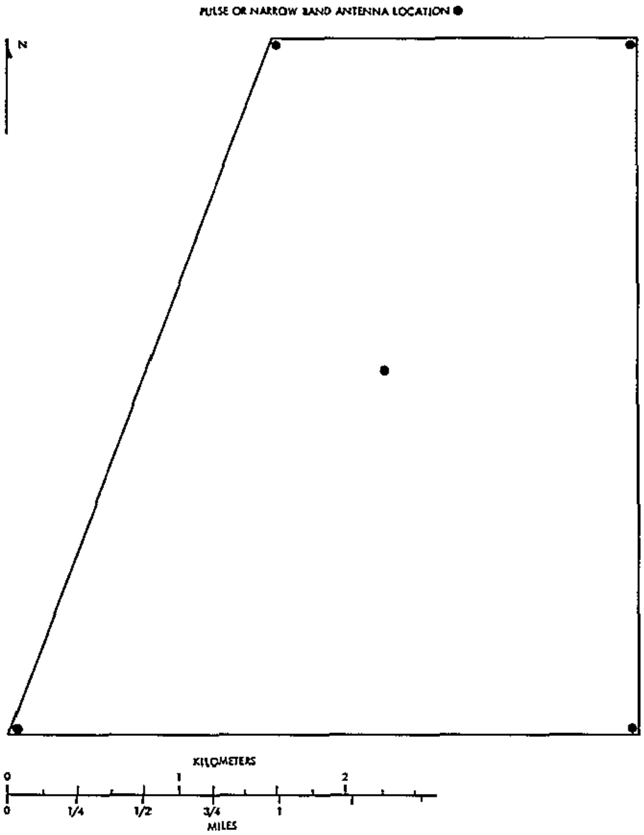

Figure 2-5. Montclair, CA, AVM Pulse or Narrow-Band Antenna Locations

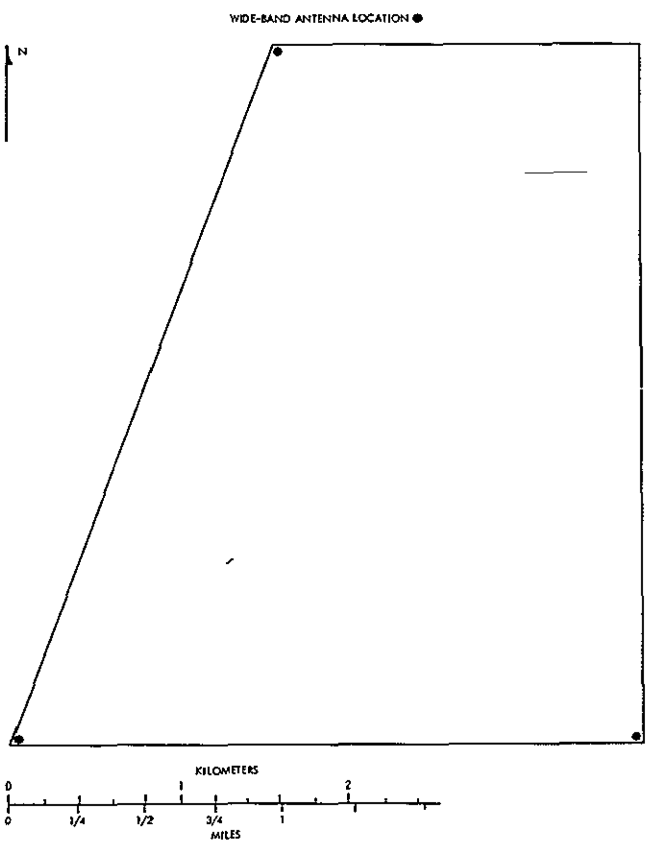

Figure 2-6. Montclair, CA, AVM Wide-Band Antenna Locations

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

AFEA IS 5.2 SQUARE MILES.

EAST WEST DISTANCE IS 2.3 MILES.

NOFTH SOUTH DISTANCE IS 2.5 MILES.

TOTAL ROAD MILEAGE IS 67 MILES.

THE NUMBER OF INTERSECTIONS IS 338.

THE ESTIMATED NUMBER OF FOAD SEGMENTS IS 506:

THEPE APE 10 CARS IN THE FLEET.

AND THEPE ARE 0 MOTOPCYCLES.

THE NUMBER OF VEHICLES ON EACH SHIFT IS:

FIRST SHIFT MAX. 5

FIRST SHIFT MIN. 4

SECOND SHIFT MAX. 5

SECOND SHIFT MIN. 4

THIPD SHIFT MAX. 7

THIRD SHIFT MIN. 7

THE NUMBER OF DISPATCHEFS IS 1

THE CITY WOULD FEQUIPE 3 WIDE+BAND OP PULSE ANTENNA SITES AND 5 NAPPOW BAND FM ANTENNA SITES FOP 7 AND 3 MILE RADIUS COVEPAGE.

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

MONTCLAIR
CLASS I

TECHNIQUE	CARS	THOUSANDS OF $ SITES	BASE	INST	O-M	VOL	TOTALS SYNC	RANDOM
KEYBOAPD	2	0	45	11	101	159	157	157
STYLUS MAP	26	0	45	11	101	133	182	132
2-ACCELEPOMETERS	16	0	63	11	101	198	200	200
LASEP VELOCIMTP	10	0	70	12	102	203	205	204
ULTPASONIC VELO	1[illegible]	0	70	11	102	197	199	149
COMPHSS/ODOMETEP	15	0	70	11	101	197	200	199
COMPHSS/LASER VEL	19	0	70	12	101	203	205	204
CMPSS/U-SONIC VEL	16	0	70	11	101	200	202	201
OMEGA	27	0	55	11	101	196	198	198
LORAN	28	0	55	11	101	197	199	149
DECCA	12	0	55	11	101	190	183	182
AM-STATIONS	4	0	55	11	101	172	174	174
DIFF. OMEGA	27	0	55	11	101	196	198	196
DIFF LORAN	23	0	55	11	101	197	199	149
DIFF. AM-STA	5	0	55	11	101	173	175	176
PELAY OMEGA	6	0	55	11	101	174	173	177
PELAY LOPAN	6	0	55	11	101	175	17[illegible]	177
CLASS II								
BUPIED RES LOOPS	2	110	45	147	101	454	455	453
PEFLECTING SIGNS	5	56	45	42	106	255	256	253
FEFLECTING ROAD	2	7	45	48	131	232	233	230
X-BAND POST	2	78	45	26	106	257	258	256
HF, VHF POST	2	9	45	15	102	173	174	171
LF POST	2	43	45	26	106	222	223	220
LIGHT/I-P POST	2	34	45	30	103	220	221	219
BUPIED MAGNETS	1	11	45	33	100	191	132	190
ULTPASONIC POST	2	44	45	54	106	251	252	249
TPAFFIC SENSOR	2	49	45	31	101	227	229	226
CLASS III								
NAR-BAND FM PHASE	3	24	54	11	103	199	201	202
WID-BAND FM PHASE	30	35	72	16	202	353	356	356
PULSE T-O-APPIVAL	26	70	143	24	17[illegible]	441	443	444
NOISE COPRELATION	3	29	143	16	177	374	375	375
DIPECTION FINDEP	1	79	35	15	154	284	282	282
CLASS IV								
TRAFFIC LOOPS	1	229	45	103	109	485	485	485
WAYSIDE PADIO	1	155	45	68	113	381	381	381
PHOTO\I-R DETECT	2	117	45	49	109	320	320	320
ULTRASONIC DETECT	2	120	45	49	109	324	324	324

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

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I TECHNIQUE	TOTAL FLEET	SIMPLE SYNC	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	1 07	0 75	0 77	1 49	0 80	0 84	1 58
		0 43	0 44	0 85	0 46	0 48	0 90
STYLUS MAP	1 12	0 78	0 80	1 52	0 87	0 91	1 64
		0 45	0 46	0 87	0 50	0 52	0 94
2-ACCELEROMETERS	1 09	0 77	0 78	1 50	0 83	0 87	1 61
		0 44	0 45	0 86	0 48	0 50	0 92
LASER VELOCIMTR	1 11	0 78	0 79	1 51	0 85	0 89	1 62
		0 44	0 45	0 86	0 49	0 51	0 93
ULTRASONIC VELO	1 09	0 77	0 78	1 50	0 83	0 87	1 61
		0 44	0 45	0 86	0 48	0 50	0 92
COMPASS/ODOMETER	1.09	0 77	0 78	1 50	0 83	0 87	1 61
		0-44	0 45	0 86	0 48	0 50	0 92
COMPASS/LASER VEL	1 09	0 77	0 78	1 50	0 83	0 87	1 61
		0 44	0 45	0 86	0 48	0 50	0 92
CMPSS/U-SONIC VEL	1 09	0 77	0 78	1 50	0 83	0 87	1 61
		0 44	0 45	0 86	0 48	0 50	0 92
OMEGA	1 18	0 83	0 85	1 56	0 95	0 99	1 73
		0 47	0 48	0 89	0 54	0 57	0 99
LORAN	1-21	0 85	0 87	1-59	1 00	1 04	1 77
		0 49	0 50	0 91	0 57	0 59	1 01
DECCA	1 20	0 84	0 86	1 58	0-98	1 02	1 75
		0 48	0 49	0 90	0 56	0 58	1-00
AM-STATIONS	1 03	0 76	0 78	1 49	0 81	0 85	1 59
		0 43	0 44	0 85	0 46	0 49	0 91
DIFF. OMEGA	1 18	0-83	0 85	1-56	0 95	0 99	1 73
		0 47	0 48	0 89	0 54	0 57	0 99
DIFF. LORAN	1-21	0 85	0 87	1 59	1 00	1 04	1 77
		0 49	0 50	0 91	0 57	0 59	1 01
DIFF AM-STA	1 17	0 82	0 84	1 56	0 94	0 98	1 72
		0 47	0 48	0 89	0 54	0 56	0 98
RELAY OMEGA	101 00	70-70	70 72	71 44	140 70	140 74	141 48
		40-40	40 41	40 82	80 40	80 42	80 84
RELAY LORAN	4 33	3 03	3 05	3 77	5 37	5 40	6 14
		1 73	1 74	2 16	3 07	3 09	3 51
CLASS II							
BURIED RES. LOOPS	1 06	0 74	0 76	1 48	0 78	0 82	1 56
		0 42	0 43	0 65	0 45	0 47	0 89
REFLECTING SIGNS	1 06	0 74	0 76	1 48	0 78	0 82	1 56
		0 42	0 43	0 85	0 45	0 47	0 89
REFLECTING ROAD	1 06	0 74	0 76	1 48	0 78	0 82	1 56
		0 42	0 43	0 85	0 45	0 47	0 89
X-BAND POST	1 06	0 74	0 76	1 48	0 78	0 82	1 56
		0 42	0 43	0 85	0 45	0 47	0 89
HF, VHF POST	1 05	0 73	0 75	1 47	0 77	0 80	1 54
		0 42	0 43	0 84	0 44	0 46	0 88
LF POST	1 06	0 74	0 76	1 48	0 78	0 82	1 56
		0 42	0 43	0 85	0 45	0 47	0 89
LIGHT/I-R POST	1 06	0 74	0 76	1 48	0 78	0 82	1 56
		0 42	0 43	0 85	0 45	0 47	0 89
BURIED MAGNETS	1 06	0 74	0 76	1 48	0 78	0 82	1 56
		0 42	0 43	0 85	0 45	0 47	0 89
ULTRASONIC POST	1 66	0 74	0 76	1 48	0 78	0 82	1 56
		0 42	0 43	0 85	0 45	0 47	0 89
TRAFFIC SENSOR	1 06	0 74	0 76	1 48	0-78	0 82	1 56
		0 42	0 43	0 85	0 45	0 47	0 89

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

MONTCLAIR

SYSTEM ACCURACIES NO. VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	30	0	89	34	0 2	0 3	-230
STYLUS MAP	30	0	77	74	0 2	0 3	-230
2-ACCELEROMETERS	34	0	91	88	0 2	0 3	-230
LASER VELOCIMTR	13	0	35	34	0 2	0 4	-210
ULTRASONIC VELO	40	0	103	100	0 2	0 3	-235
COMPASS/ODOMETER	20	0	50	48	0 2	0 4	-205
COMPASS/LASER VEL	15	0	39	38	0 2	0 4	-305
CMPSS/U-SONIC VEL	17	0	43	42	0 2	0 4	-205
OMEGA	1500	0	3751	3664	0 0	0 0	0
LORAN	160	0	375	367	0 0	0 0	0
DECCA	200	0	452	442	0 0	0.0	0
AM-STATIONS	200	0	450	440	0 0	0 0	0
DIFF OMEGA	160	0	375	366	0 0	0 0	0
DIFF LORAN	400	0	983	945	0 0	0 0	0
DIFF AM-STA	250	0	545	532	0 0	0 0	0
RELAY OMEGA	500	0	2446	1392	0 0	0 0	0
RELAY LORAN	300	0	2110	2053	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	0	27	27	0 2	0 4	-205
REFLECTING SIGNS	10	0	27	27	0 2	0 4	-200
REFLECTING ROAD	3	0	27	15	0 2	0 4	-305
X-BAND POST	12	0	32	32	0 2	0 4	-230
HF VHF POST	15	0	39	38	0 2	0 4	-210
LF POST	100	0	245	239	0 0	0 0	0
LIGHT/I-R POST	30	0	77	74	0 2	0 3	-320
BURIED MAGNETS	[illegible]	0	27	15	0 2	0 4	-200
ULTRASONIC POST	20	0	50	40	0 2	0 4	-200
TRAFFIC SENSOR	10	0	27	27	0 2	0 4	-205
CLASS III							
NAR-BAND FM PHASE	1000	0	2370	2306	0 0	0 0	0
MID-BAND FM PHASE	1200	0	2814	2739	0 0	0 0	0
PULSE T-O-ARRIVAL	100	0	169	164	0 1	0 1	-315
NOISE CORRELATION	100	0	169	193	0 1	0.1	-310
DIRECTION FINDER	700	0	1743	1697	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	0	26	26	0 2	0 4	-245
WAYSIDE RADIO	100	0	230	237	0 0	0 0	0
PHOTO/I-R DETECT	30	0	70	73	0 2	0 3	-320
ULTRASONIC DETECT	20	0	47	43	0 2	0 4	-245

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

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

AREA IS 7.3 SQUARE MILES.

EAST WEST DISTANCE IS 4.6 MILES.

NORTH SOUTH DISTANCE IS 3 MILES.

TOTAL ROAD MILEAGE IS 101 MILES.

THE NUMBER OF INTERSECTIONS IS 596.

THE ESTIMATED NUMBER OF ROAD SEGMENTS IS 226:

THERE ARE 15 CARS IN THE FLEET.

AND THERE ARE 0 MOTORCYCLES.

THE NUMBER OF VEHICLES ON EACH SHIFT IS:

FIRST SHIFT MAX. 14

FIRST SHIFT MIN. 4

SECOND SHIFT MAX. 14

SECOND SHIFT MIN. 4

THIRD SHIFT MAX. 14

THIRD SHIFT MIN. 4

THE NUMBER OF DISPATCHERS IS 1

THE CITY WOULD REQUIRE 5 WIDE+BAND OR PULSE ANTENNA SITES AND 5 NARROW BAND FM ANTENNA SITES FOR 7 AND 3 MILE RADIUS COVERAGE.

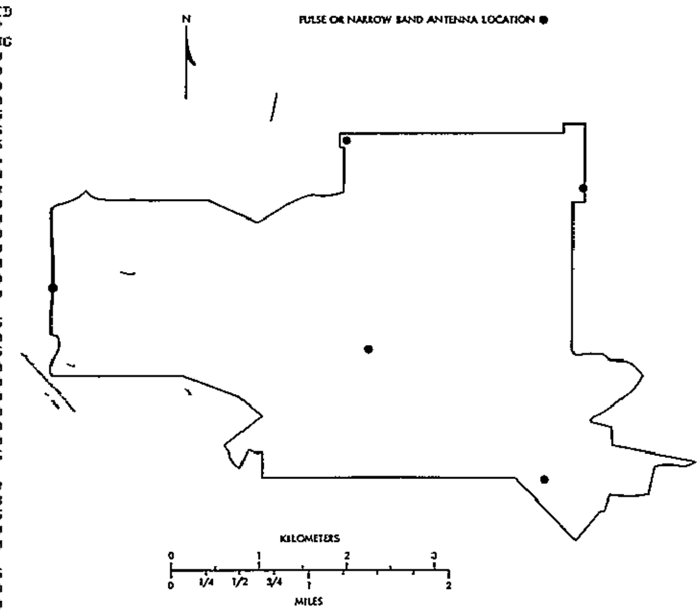

Figure 2-7. Monterey Park, CA, AVM Pulse or Narrow-Band Antennas

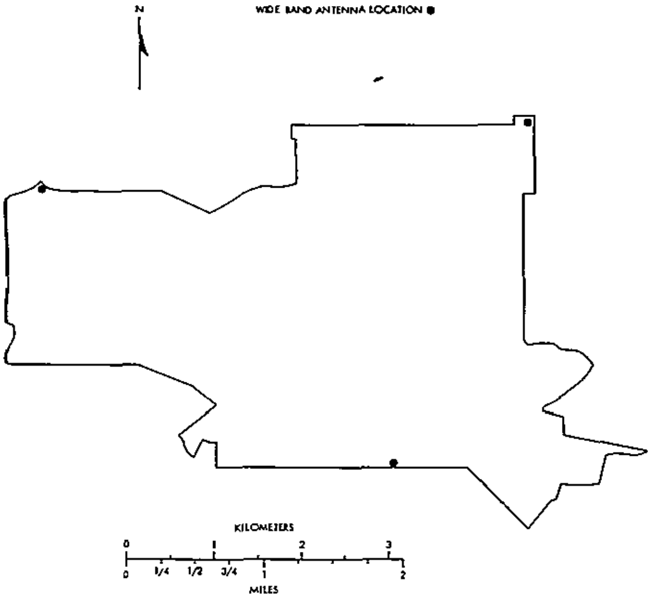

Figure 2-8. Monterey Park, CA, AVM Wide-Band Antenna Locations

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

MONTEREY PARK
CLASS I

TECHNIQUE	CARS	SITES (THOUSANDS OF $)	BASE	INST	O-M	VOL (TOTALS)	SYNC	RANDOM
KEYBOARD	3	0	48	11	131	164	161	161
STYLUS MAP	39	0	43	11	101	200	198	190
2-ACCELEROMETERS	24	0	72	12	102	212	215	214
LASER VELOCIMTR	27	0	75	13	103	219	222	221
ULTRASONIC VELO	20	0	75	12	103	211	214	213
COMPASS/ODOMETER	22	0	75	11	101	211	214	212
COMPASS/LASER VEL	28	0	75	13	102	219	223	221
CMPSS/U-SONIC VEL	24	0	75	12	102	215	218	217
OMEGA	41	0	60	12	102	216	220	219
LORAN	42	0	60	12	102	217	221	221
DECCA	10	0	60	11	102	192	196	195
AM-STATIONS	6	0	60	11	101	181	183	183
DIFF OMEGA	41	0	60	12	102	216	219	219
DIFF. LORAN	42	0	60	12	102	217	220	221
DIFF AM-STA	7	0	60	11	101	182	184	186
RELAY OMEGA	8	0	60	12	102	183	181	187
RELAY LORAN	9	0	60	12	102	184	182	186
CLASS II								
BURIED RES LOOPS	3	149	46	348	101	699	701	697
REFLECTING SIGNS	3	91	43	62	109	319	321	317
REFLECTING ROAD	2	10	46	71	150	283	284	280
X-BAND POST	3	138	48	33	110	337	338	335
HF, VHF POST	3	15	48	18	103	190	194	195
LF POST	3	75	48	30	110	274	276	272
LIGHT/I-R POST	3	60	48	44	116	272	273	269
BURIED MAGNETS	2	20	48	51	100	223	224	220
ULTRASONIC POST	3	71	43	62	109	313	315	311
TRAFFIC SENSOR	3	74	43	44	101	275	277	273
CLASS III								
MAP-BAND FM PHASE	4	24	71	12	100	212	216	216
MID-BAND FM PHASE	44	35	31	16	202	378	381	302
PULSE T-O-ARRIVAL	39	70	175	25	170	437	440	441
NOISE CORRELATION	12	29	175	16	177	411	412	413
DIRECTION FINDER	1	79	41	15	154	240	239	229
CLASS IV								
TRAFFIC LOOPS	[illegible]	375	48	172	115	711	711	711
WAYSIDE RADIO	2	234	48	104	121	503	503	503
PHOTO/I-R DETECT	2	137	48	79	116	430	430	430
ULTRASONIC DETECT	2	133	48	79	116	436	406	436

Table 2-15. Monterey Park, CA, AVM Polling Cycle Min/Max Times

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I TECHNIQUE	TOTAL FLEET	SIMPLE SYNC	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	1 61	1 58	1 54	2 98	1 61	1 66	3 16
		0 43	0 44	0 05	0 46	0 43	0 90
STYLUS MAP	1 68	1 57	1.61	3 04	1 74	1.81	3 29
		0 45	0 46	0 87	0 50	0 52	0 94
2-ACCELEROMETERS	1 64	1 53	1 57	3 01	1 66	1 74	3 21
		0 44	0 45	0 86	0 48	0 50	0 92
LASER VELOCIMTR	1 66	1.55	1 59	3 02	1.70	1 77	3 25
		0 44	0 45	0 86	0 49	0 51	0 93
ULTRASONIC VELO	1 64	1 53	1.57	3 01	1 66	1 74	3 21
		0 44	0 45	0 86	0 48	0 50	0 92
COMPASS/ODOMETER	1 64	1 53	1 57	3 01	1 66	1 74	3 21
		0 44	0 45	0 86	0 48	0 50	0 92
COMPASS/LASER VEL	1 64	1 53	1 57	3 01	1 66	1 74	3 21
		0 44	0 45	0 86	0 48	0 50	0 92
CMPSS/U-SONIC VEL	1 64	1.53	1 57	3 01	1 66	1 74	3 21
		0 44	0 45	0 86	0.48	0.50	0 92
OMEGA	1.77	1 65	1.69	3 13	1.90	1 98	3 45
		0 47	0 48	0 89	0 54	0 57	0 99
LORAN	1 82	1 70	1 74	3 17	2 00	2 07	3 55
		0 49	0 50	0 91	0 57	0 59	1 01
DECCA	1 80	1 68	1 72	3 16	1 96	2 03	3 51
		0 48	0 49	0.90	0 56	0 58	1 00
AM-STATIONS	1 62	1 51	1 55	2 99	1 62	1 70	3 17
		0 43	0 44	0 85	0 46	0.49	0 91
DIFF OMEGA	1.77	1 65	1 69	3 13	1 90	1 98	3 45
		0 47	0 48	0 89	0 54	0 57	0 99
DIFF LORAN	1 82	1 70	1 74	3 17	2 00	2 07	3 55
		0 49	0 50	0 91	0 57	0 59	1 01
DIFF. AM-STA	1 76	1.64	1 68	3 12	1.89	1 96	3 44
		0 47	0 48	0 89	0 54	0 56	0 98
RELAY OMEGA	151.50	141 40	141 44	142 88	281 40	281 47	282 95
		40 40	40 41	40 82	80 40	80 42	80 84
RELAY LORAN	6 50	6 07	6 10	7 54	10 73	10 81	12 28
		1 73	1 74	2.16	3 07	3 09	3 51
CLASS II							
BURIED RES LOOPS	1 60	1 49	1 53	2 97	1 59	1 66	3 14
		0 43	0 44	0 85	0 45	0 48	0 90
REFLECTING SIGNS	1.60	1.49	1 53	2 97	1 59	1 66	3 14
		0 43	0 44	0 85	0 45	0 48	0 90
REFLECTING ROAD	1 60	1 49	1 53	2 97	1 59	1 66	3 14
		0 43	0 44	0 85	0 45	0 48	0 90
X-BAND POST	1 60	1.49	1 53	2.97	1 59	1 66	3 14
		0 43	0 44	0 85	0 45	0 48	0 90
HF, VHF POST	1 58	1 47	1 51	2 95	1 55	1 62	3 10
		0 42	0 43	0 84	0 44	0 46	0 89
LF POST	1 60	1 49	1 53	2 97	1 59	1 66	3 14
		0 43	0 44	0 85	0 45	0 48	0 90
LIGHT/I-R POST	1 60	1 49	1 53	2 97	1 59	1 66	3 14
		0 43	0 44	0 85	0 45	0 48	0 90
BURIED MAGNETS	1 60	1 49	1 53	2 97	1 59	1 66	3 14
		0 43	0 44	0 85	0 45	0 48	0 90
ULTRASONIC POST	1 60	1 49	1.53	2 97	1 59	1 66	3 14
		0 43	0 44	0 85	0 45	0 48	0 90
TRAFFIC SENSOR	1 60	1 49	1 53	2 97	1 59	1 66	3 14
		0 43	0 44	0 85	0 45	0 48	0 90

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Table 2-16. Monterey Park, CA, AVM Accuracies and Cost Benefits

MONTEREY PARK
SYSTEM ACCURACIES AT VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEN VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	1	92	[illegible]	0 2	0 5	-131
STYLUS MAP	30	1	81	74	0 2	0 6	-75
2-ACCELEROMETERS	54	1	96	93	0 2	0 5	-155
LASER VELOCIMTR	13	1	56	34	0 2	0 7	10
ULTRASONIC VELO	40	1	106	100	0 2	0 5	-140
COMPASS/ODOMETER	20	1	56	48	0 2	0 7	20
COMPASS/LASER VEL	15	1	35	33	0 2	0 7	15
CMPSS/U-SONIC VEL	17	1	55	42	0 2	0 7	15
OMEGA	1500	0	3561	3664	0 0	0 0	0
LORAN	140	0	337	367	0 0	0 0	0
DECCA	200	0	466	442	0 0	0 0	0
AM-STATIONS	200	0	464	440	0 0	0 0	0
DIFF OMEGA	160	0	386	366	0 0	0 0	0
DIFF LORAN	400	0	1065	945	0 0	0 0	0
DIFF AM-STA	250	0	561	532	0 0	0 0	0
RELAY OMEGA	500	0	4755	1342	0 0	0 0	0
RELAY LORAN	300	0	2102	2053	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	1	53	27	0 2	0 7	-20
REFLECTING SIGNS	10	1	53	27	0 2	0 7	-20
REFLECTING ROAD	3	1	52	15	0 2	0 7	-225
X-BAND POST	12	1	54	32	0 2	0 7	-25
HF VHF POST	15	1	53	[illegible]	0 2	0 7	10
LF POST	100	1	254	234	0 1	0 6	-475
LIGHT/I-R POST	30	1	80	74	0 2	0 6	-130
BURIED MAGNETS	[illegible]	1	52	15	0 2	0 7	25
ULTRASONIC POST	20	1	51	43	0 2	0 7	-20
TRAFFIC SENSOR	10	1	53	27	0 2	0 7	20
CLASS III							
MAP-BAND FM PHASE	1000	0	2451	2306	0 0	0 0	0
MID-BAND FM PHASE	1200	0	2911	2739	0 0	0 0	0
PULSE T-O-ARRIVAL	100	1	174	164	0 1	0 2	-740
NOISE CORRELATION	100	1	145	133	0 1	0 1	-610
DIRECTION FINDER	700	0	1803	1697	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	1	25	26	0 2	0 3	25
WAYSIDE RADIO	100	1	223	237	0 1	0 6	-530
PHOTO/I-R DETECT	30	1	67	73	0 2	0 6	-130
ULTRASONIC DETECT	20	1	46	48	0 2	0 7	-75

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

Table 2-17. Pasadena, CA, City AVM Physical Parameters

AREA IS 23 SQUARE MILES.

EAST WEST DISTANCE IS 6 MILES.

NORTH SOUTH DISTANCE IS 5 MILES.

TOTAL ROAD MILEAGE IS 350 MILES.

THE NUMBER OF INTERSECTIONS IS 1260.

THE ESTIMATED NUMBER OF ROAD SEGMENTS IS 2720:

THERE ARE 35 CARS IN THE FLEET.

AND THERE ARE 0 MOTORCYCLES.

THE NUMBER OF VEHICLES ON EACH SHIFT IS:

FIRST SHIFT MAX. 10

FIRST SHIFT MIN. 10

SECOND SHIFT MAX. 10

SECOND SHIFT MIN. 10

THIRD SHIFT MAX. 10

THIRD SHIFT MIN. 10

THE NUMBER OF DISPATCHERS IS 1

THE CITY WOULD REQUIRE 3 WIDE-BAND OR

PULSE ANTENNA SITES AND 7 NARROW BAND

FM ANTENNA SITES FOR 7 AND ? MILE RADIUS COVERAGE.

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

PASADENA

		THOUSANDS OF $					TOTALS	
TECHNIQUE	CHPS	SITES	BASE	INST	O-M	MUL	SYNC	RANDOM
CLASS I								
KEYBOARD	5	0	57	12	101	120	174	174
STYLUS MAP	40	0	57	12	101	244	[illegible]	259
2-ACCELEROMETERS	56	0	79	14	104	253	265	[illegible]
LASER VELOCIMTR	65	0	87	15	106	275	282	281
ULTRASONIC VELO	45	0	87	14	106	256	263	261
COMPASS/ODOMETER	52	0	87	11	102	256	265	261
COMPASS/LASER VEL	65	0	87	16	104	276	235	281
CMPSS/U-SONIC VEL	56	0	87	14	104	265	274	270
OMEGA	95	0	72	13	103	288	297	295
LORAN	96	0	72	13	103	292	301	299
DECCA	41	0	72	13	103	233	242	241
AM-STATIONS	14	0	72	12	103	206	213	211
DIFF OMEGA	95	0	72	13	103	288	295	245
DIFF LORAN	98	0	72	13	103	292	290	249
DIFF AM-STA	17	0	72	12	100	200	215	[illegible]
RELAY OMEGA	19	0	72	13	104	213	207	221
RELAY LORAN	21	0	72	13	104	215	204	220
CLASS II								
BURIED RES LOOPS	5	1072	57	1833	101	3073	3076	3067
REFLECTING SIGNS	17	410	57	239	133	865	869	860
REFLECTING ROAD	5	45	57	280	324	716	719	710
Y-BAND POST	6	428	57	96	129	720	724	715
HF, VHF POST	6	47	57	63	103	255	258	249
LF PULT	6	223	57	16	129	525	528	719
LIGHT/I-R POST	6	186	57	115	148	516	520	511
BURIED MAGNETS	4	108	57	226	100	500	503	494
ULTRASONIC POST	5	317	57	330	139	851	855	[illegible]
TRAFFIC SENSOR	6	354	57	161	101	682	685	677
CLASS III								
VHF-BAND FM PHASE	8	33	90	13	105	257	265	266
WID-BAND FM PHASE	102	35	105	13	203	462	471	472
PULSE T-O-ARRIVAL	91	98	240	33	180	649	657	658
NOISE CORRELATION	28	29	249	18	178	505	509	509
DIRECTION FINDER	2	79	54	16	154	307	313	303
CLASS IV								
TRAFFIC LOOPS	3	1637	57	517	145	2350	2353	2350
WAYSIDE RADIO	3	1413	57	432	194	2097	2097	2097
PHOTO\I-R DETECT	5	534	57	223	140	1315	1315	1315
ULTRASONIC DETECT	5	413	57	223	143	1334	1334	1334

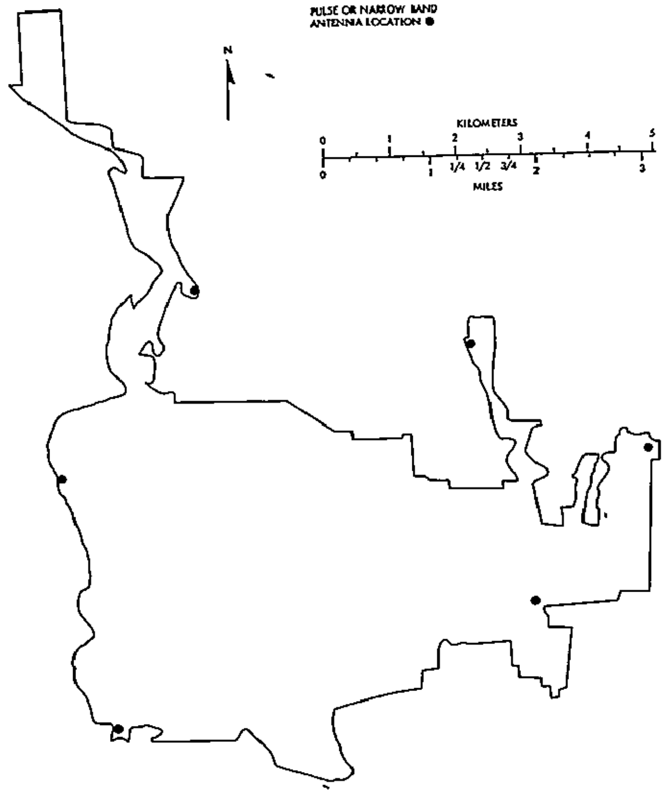

Figure 2-9. Pasadena, CA, AVM Pulse or Narrow-Band Antenna Locations

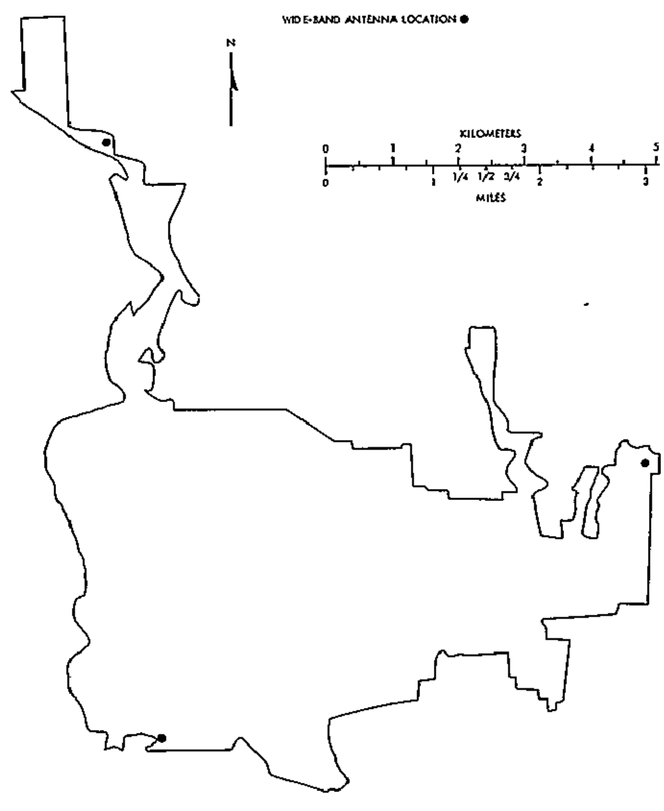

Figure 2-10. Pasadena, CA, AVM Wide-Band Antenna Locations

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

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I TECHNIQUE	TOTAL FLEET	SIMPLE SYNC	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	3 76	1 07	1.11	2 15	1 15	1 23	2 31
		1 07	1 11	2 15	1 15	1 23	2 31
STYLUS MAP	3 92	1 12	1.16	2 20	1 24	1 32	2 40
		1 12	1 16	2 20	1 24	1 32	2 40
2-ACCELEROMETERS	3 83	1 09	1 13	2 17	1 19	1 27	2 35
		1 09	1 13	2 17	1 19	1 27	2 35
LASER VELOCIMTR	3 87	1 11	1 15	2 19	1 21	1 29	2 37
		1 11	1 15	2 19	1 21	1 29	2 37
ULTRASONIC VELO	3 83	1 09	1 13	2 17	1 19	1 27	2 35
		1 09	1 13	2 17	1-19	1 27	2 35
COMPASS/ODOMETER	3 83	1 09	1 13	2 17	1 19	1 27	2 35
		1 09	1-13	2 17	1-19	1 27	2-35
COMPASS/LASER VEL	3 83	1 09	1-13	2 17	1 19	1 27	2 35
		1 09	1 13	2 17	1 19	1 27	2 35
CMPSS/U-SONIC VEL	3 83	1 09	1 13	2 17	1 19	1 27	2 35
		1 09	1 13	2 17	1 19	1 27	2 35
OMEGA	4 13	1 18	1 22	2 26	1 36	1 44	2 52
		1 18	1 22	2 26	1 36	1 44	2 52
LORAN	4 25	1 21	1 25	2 29	1 43	1.51	2 59
		1 21	1 25	2 29	1 43	1 51	2 59
DECCA	4 28	1 20	1 24	2 28	1 48	1 48	2 56
		1 20	1 24	2 28	1 48	1 48	2 56
AM-STATIONS	3 78	1 08	1 12	2 16	1 16	1 24	2 32
		1.08	1 12	2.16	1 16	1 24	2 32
DIFF OMEGA	4 13	1 18	1 22	2 26	1 36	1 44	2 52
		1.18	1 22	2 26	1 36	1 44	2 52
DIFF. LORAN	4.25	1 21	1 25	2 29	1 43	1 51	2 59
		1 21	1 25	2 29	1 43	1 51	2 59
DIFF AM-STA	4 11	1 17	1 21	2 25	1 35	1 43	2 51
		1 17	1 21	2 25	1 35	1 43	2 51
RELAY OMEGA	353 58	101 08	101 04	102 08	201 08	201 08	202 16
		101.08	101 04	102.08	201 08	201 08	202 16
RELAY LORAN	15 17	4 33	4 37	5 41	7 67	7 75	8 83
		4 33	4 37	5 41	7 67	7 75	8 83
CLASS II							
BURIED RES LOOPS	3 78	1 08	1 12	2 16	1 16	1 24	2 32
		1 08	1 12	2 16	1 16	1 24	2 32
REFLECTING SIGNS	3 78	1 08	1.12	2 16	1 16	1 24	2 32
		1 08	1 12	2 16	1 16	1 24	2 32
REFLECTING ROAD	3 78	1 08	1 12	2 16	1 16	1 24	2 32
		1.08	1 12	2.16	1 16	1 24	2 32
X-BAND POST	3 76	1 07	1 11	2 15	1 15	1 23	2 31
		1 07	1 11	2 15	1 15	1 23	2 31
HF, VHF POST	3 71	1 06	1 10	2 14	1 12	1 20	2 28
		1 06	1 10	2 14	1 12	1 20	2 28
LF POST	3 76	1.07	1 11	2 15	1 15	1 23	2 31
		1 07	1 11	2 15	1 15	1 23	2 31
LIGHT/I-R POST	3 76	1 07	1 11	2 15	1 15	1 23	2 31
		1 07	1 11	2 15	1 15	1 23	2 31
BURIED MAGNETS	3 78	1 08	1 12	2 16	1 16	1 24	2 32
		1 08	1 12	2 16	1 16	1 24	2 32
ULTRASONIC POST	3 76	1 07	1 11	2 15	1.15	1 23	2 31
		1 07	1.11	2 15	1.15	1 23	2 31
TRAFFIC SENSOR	3 76	1 07	1 11	2 15	1 15	1 23	2 31
		1 07	1.11	2 15	1 15	1 23	2 31

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

PASADENA

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	1	90	90	0 5	0 5	-120
STYLUS MAP	30	1	74	79	0 5	0 5	-130
2-ACCELEROMETERS	34	1	44	44	0 5	0 5	-145
LASER VELOCIMTR	13	1	41	41	0 6	0 6	-80
ULTRASONIC VELO	40	1	104	104	0 5	0 5	-155
COMPASS/ODOMETER	20	1	50	50	0 6	0 6	-60
COMPASS/LASER VEL	15	1	40	40	0 6	0 6	-70
CMPSS/U-SONIC VEL	17	1	44	44	0 6	0 6	-70
OMEGA	1600	0	3310	3310	0 0	0 0	0
LORAN	160	0	381	381	0 1	0 1	-40
DECCA	200	0	460	460	0 0	0 0	0
AM-STATIONS	200	0	450	450	0 0	0 0	0
DIFF OMEGA	150	0	381	391	0 1	0 1	-40
DIFF LORAN	400	0	1050	1050	0 0	0 0	0
DIFF AM-STA	250	0	553	553	0 0	0 0	0
RELAY OMEGA	500	0	3466	3466	0 0	0 0	0
RELAY LORAN	500	0	2147	2147	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	1	40	0	0 6	0 6	-55
REFLECTING SIGNS	10	1	40	40	0 6	0 6	-240
REFLECTING ROAD	3	1	39	39	0 6	0 6	-1170
X-BAND POST	12	1	40	40	0 6	0 6	-195
HF, VHF POST	15	1	40	40	0 6	0 6	-30
LF POST	100	1	250	250	0 3	0 3	-420
LIGHT/I-R POST	30	1	79	79	0 5	0 5	-365
BURIED MAGNETS	4	1	39	39	0 6	0 6	-50
ULTRASONIC POST	20	1	50	50	0 6	0 6	-245
TRAFFIC SENSOR.	10	1	40	40	0 6	0 6	-55
CLASS III							
NAR-BAND FM PHASE	1000	0	2411	2411	0 0	0 0	0
WID-BAND FM PHASE	1200	0	2864	2864	0 0	0 0	0
PULSE T-O-ARRIVAL	100	1	172	172	0 4	0 4	-600
NOISE CORRELATION	100	1	192	192	0 4	0 4	-590
DIRECTION FINDER	700	0	1774	1774	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	1	25	25	0 6	0 6	-275
WAYSIDE RADIO	100	1	226	226	0 3	0 3	-745
PHOTO/I-R DETECT	30	1	66	63	0 6	0 6	-290
ULTRASONIC DETECT	20	1	46	46	0 6	0 6	-290

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

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

AREA IS 331 SQUARE MILES.

EAST WEST DISTANCE IS 23.6 MILES.

NORTH SOUTH DISTANCE IS 41.2 MILES.

TOTAL ROAD MILEAGE IS 1945 MILES.

THE NUMBER OF INTERSECTIONS IS 13700:

THE ESTIMATED NUMBER OF ROAD SEGMENTS IS 27400.

THERE ARE 300 CARS IN THE FLEET

AND THERE ARE 52 MOTORCYCLES.

THE NUMBER OF VEHICLES ON EACH SHIFT IS.

FIRST SHIFT MAX. 66

FIRST SHIFT MIN 66

SECOND SHIFT MAX. 95

SECOND SHIFT MIN. 95

THIRD SHIFT MAX. 60

THIRD SHIFT MIN. 60

THE CITY WOULD REQUIRE 23 WIDE-BAND OR

PULSE T-O-A ANTENNA SITES AND 85 NARROW

BAND ANTENNA SITES WITH 7 AND 3 MILE COVERAGE RADII.

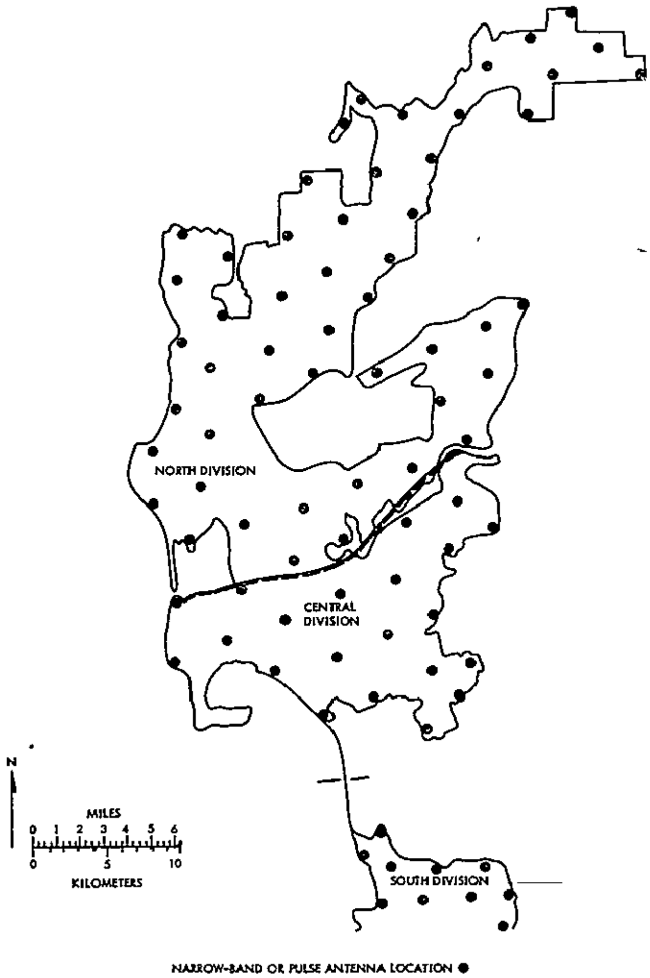

Figure 2-11. San Diego, CA, AVM Pulse or Narrow-Band Antenna Locations

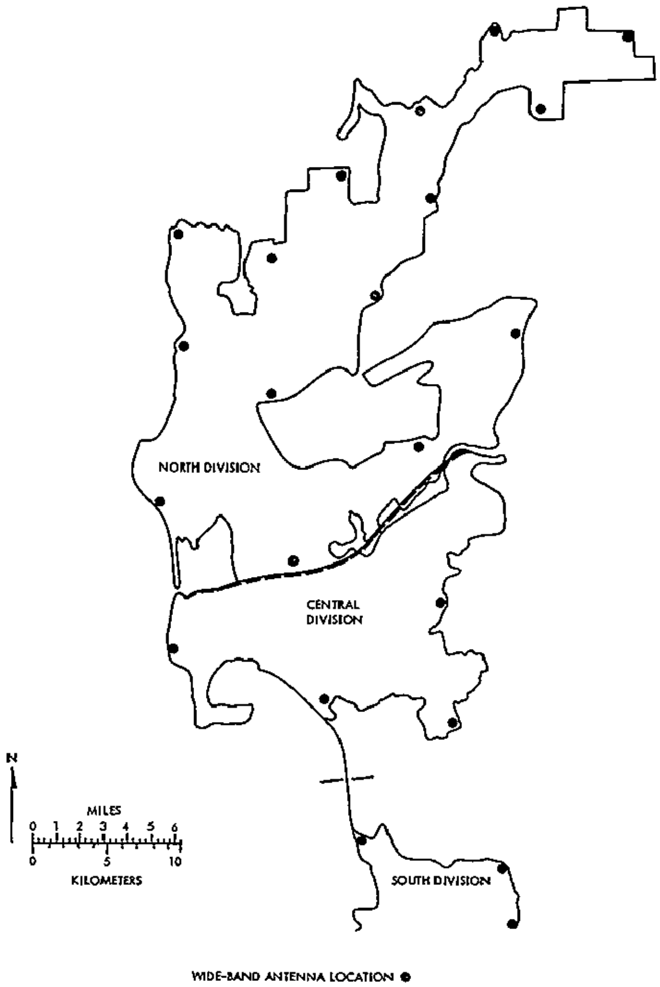

Figure 2-12. San Diego, CA, AVM Wide-Band Antenna Locations

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

SAN DIEGO

CLASS I TECHNIQUE	CHPS	SITES	BASE	INST	O-M	VOL	SYNC	RANDOM
	THOUSANDS OF $						TOTALS	
KEYBOARD	41	0	39	21	105	303	255	255
STYLUS MAP	765	0	39	21	108	1050	982	902
2-ACCELEROMETERS	480	0	120	40	130	826	886	871
LASER VELOCIMTR	534	0	126	51	145	406	965	950
ULTRASONIC VELO	381	0	120	40	145	742	302	787
COMPASS/ODOMETER	440	0	128	16	112	744	316	735
COMPASS/LASER VEL	557	0	120	55	127	915	487	456
CMPSS/U-SONIC VEL	476	0	119	40	127	810	282	351
OMEGA	810	0	109	34	123	1124	1203	1185
LORAN	840	0	109	34	123	1154	1233	1221
DECCA	345	0	109	28	123	653	702	717
AM-STATIONS	120	0	109	25	110	420	477	463
DIFF OMEGA	810	0	109	34	123	1124	1161	1185
DIFF LORAN	840	0	109	34	123	1154	1211	1221
DIFF AM-STA	140	0	109	25	118	440	497	527
RELAY OMEGA	158	0	109	34	130	477	431	551
RELAY LORAN	173	0	109	34	130	494	446	566
CLASS II								
BURIED RES LOOPS	42	9864	39	16793	105	26940	26969	26892
REFLECTING SIGNS	144	3014	89	1699	380	5374	5400	5326
REFLECTING ROAD	38	229	89	2001	1749	4253	4282	4205
X-BAND POST	51	3151	89	639	309	4206	4315	4203
HF VHF POST	47	346	89	177	155	357	305	349
LF POST	45	1713	89	640	310	2845	2873	2797
LIGHT/I-R POST	44	1370	89	786	450	2707	2815	2709
BURIED MAGNETS	30	987	89	1997	100	3250	3279	3202
ULTRASONIC POST	41	2329	89	2365	382	5055	5281	5205
TRAFFIC SENSOR	44	2603	89	1110	103	4005	4030	3957
CLASS III								
NAR-BAND FM PHASE	65	400	176	60	150	356	931	909
WID-BAND FM PHASE	372	267	176	72	219	1005	1683	1667
PULSE T-O-ARRIVAL	773	1190	357	268	225	2812	2887	2895
NOISE CORRELATION	236	29	357	45	134	398	925	932
DIRECTION FINDER	11	80	112	19	154	411	375	375
CLASS IV								
TRAFFIC LOOPS	34	15550	89	3745	432	19840	19840	19840
WAYSIDE RADIO	23	13593	89	3119	778	17611	17611	17611
PHOTO/I-R DETECT	35	8767	89	1530	447	10917	10917	10917
ULTRASONIC DETECT	38	6904	89	1578	447	11055	11055	11055

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

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I TECHNIQUE	TOTAL FLEET	SIMPLE SYNC	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	37 78	10 20	10 77	20 84	10 89	12 03	22 67
		6 44	6 00	13 16	6 88	7 60	14 32
STYLUS MAP	39 42	10 64	11 21	21 28	11 78	12 92	23 56
		6 72	7 03	13 44	7 44	8 16	14 88
2-ACCELEROMETERS	38 49	10 39	10 96	21 03	11 27	12 41	23 05
		6 56	6 92	13 28	7.12	7 84	14 56
LASER VELOCIMTR	38 95	10 51	11 03	21 15	11 50	12 67	23 31
		6 64	7 00	13 36	7 28	8 00	14 72
ULTRASONIC VELO	38 49	10 39	10 96	21 00	11 27	12 41	23 05
		6 56	6 92	13 28	7.12	7 84	14 56
COMPASS/ODOMETER	38 49	10 39	10 96	21 03	11 27	12 41	23 05
		6 56	6 42	13 28	7 12	7 84	14 56
COMPASS/LASER VEL	38 49	10 39	10 96	21 03	11 27	12 41	23 05
		6 56	6 92	13 28	7.12	7 84	14 56
CMPSS/U-SONIC VEL	38 49	10 39	10 96	21 03	11 27	12 41	23 05
		6 56	6 92	13 28	7 12	7 84	14 56
OMEGA	41 54	11 21	11 78	21 85	12 92	14 06	24 70
		7 08	7 44	13 80	8 16	8 88	15 60
LORAN	42 71	11 53	12 10	22 17	13 55	14 69	25 33
		7 23	7 64	14 00	8 56	9 28	16 00
DECCA	42 24	11 40	11 97	22 04	13 30	14 44	25 08
		7 20	7 56	13 92	8 40	9 12	15 84
AM-STATIONS	38 02	10 26	10 83	20 90	11 02	12 16	22 30
		6 48	6 84	13 20	6 96	7 68	14 40
DIFF OMEGA	41 54	11 21	11 78	21 85	12 92	14 06	24 70
		7 08	7 44	13 80	8 16	8 88	15 60
DIFF LORAN	42 71	11 53	12 10	22 17	13 55	14 69	25 33
		7 28	7 64	14 00	8 56	9 28	16 00
DIFF AM-STA	41 30	11 15	11 72	21 79	12 79	13 93	24 57
		7 04	7 40	13 76	8 08	8 80	15 52
RELAY OMEGA	3555 20	959 50	960 07	970 14	1909 50	1910 64	1921 28
		606 00	606 36	612 72	1206 00	1206 72	1213 44
RELAY LORAN	152 53	41 17	41 74	51 81	72 83	73 97	84 61
		26 00	26 36	32 72	46 00	46 72	53 44
CLASS II							
BURIED RES LOOPS	38 72	10 45	11 02	21 09	11 40	12 54	23 18
		6 60	6 96	13 32	7 20	7 92	14.64
REFLECTING SIGNS	38 72	10 45	11 02	21 09	11 40	12 54	23 18
		6 60	6 96	13 32	7 20	7.92	14 64
REFLECTING ROAD	38 72	10 45	11 02	21 09	11 40	12 54	23 18
		6 60	6 96	13 32	7 20	7.92	14.64
X-BAND POST	38 49	10 39	10 96	21 03	11 27	12 41	23 05
		6 56	6 92	13 28	7 12	7.84	14 56
HF, VHF POST	38 02	10 26	10 83	20 90	11 02	12 16	22 30
		6 48	6 84	13 20	6 96	7 68	14 40
LF POST	38 49	10 39	10 96	21 03	11 27	12 41	23 05
		6 56	6 92	13 28	7 12	7 84	14 56
LIGHT/I-R POST	38 49	10 39	10 96	21 03	11 27	12 41	23 05
		6 56	6 92	13 28	7 12	7 84	14 56
BURIED MAGNETS	38 72	10 45	11 02	21 09	11 40	12 54	23 18
		6 60	6 96	13 32	7.20	7 92	14 64
ULTRASONIC POST	38 49	10 39	10 96	21 03	11 27	12 41	23 05
		6 56	6 92	13 28	7.12	7 34	14 56
TRAFFIC SENSOR	38 49	10 39	10 96	21 03	11 27	12 41	23 05
		6 56	6 92	13 28	7 12	7 84	14.56

1

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

SAN DIEGO

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	6	382	245	2 8	2 4	1575
STYLUS MAP	30	6	345	253	2 7	2 2	1435
2-ACCELEROMETERS	34	6	383	249	2 8	2 3	1450
LASER VELOCIMTR	13	7	381	244	2 8	2 4	1575
ULTRASONIC VELO	40	6	390	250	2 8	2 3	1575
COMPASS/ODOMETER	20	6	302	245	2 8	2 4	1540
COMPASS/LASER VEL	15	6	379	243	2 8	2 4	1465
CMPSS/U-SONIC VEL	17	6	388	244	2 8	2 4	1455
OMEGA	1600	0	4142	4112	0 0	0 0	0
LORAN	160	5	443	412	1.9	1 7	910
DECCA	200	4	506	496	1 4	1 0	405
AM-STATIONS	200	4	505	494	1 4	1 0	400
DIFF OMEGA	160	5	419	411	1 9	2 0	305
DIFF LORAN	400	2	1167	1142	0 0	0 0	0
DIFF AM-STA	250	4	614	597	0 5	0 0	19
RELAY OMEGA	500	1	33040	28969	0 0	0 0	0
RELAY LORAN	500	3	2143	2343	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	7	377	241	2 8	2 4	1575
REFLECTING SIGNS	10	7	377	241	2 8	2 4	[illegible]
REFLECTING ROAD	3	7	364	233	2 9	2 6	-6570
X-BAND POST	12	7	377	241	2 8	2 4	555
HF, VHF POST	15	6	375	240	2 8	2 4	1025
LF POST	150	6	400	273	2 6	2 2	40
LIGHT/I-R POST	[illegible]	6	307	243	2 8	2 0	-158
BURIED MAGNETS	4	7	367	235	2 8	2 5	1600
ULTRASONIC POST	20	6	382	245	2 8	2 4	1440
TRAFFIC SENSOR	10	7	375	240	2 8	2 5	1535
CLASS III							
NAR-BAND FM PHASE	1000	0	2690	2630	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3167	3106	0 0	0 0	0
PULSE T-O-ARRIVAL	100	6	191	187	3 1	4 5	2250
NOISE CORRELATION	100	6	214	209	3 0	4 2	2230
DIRECTION FINDER	700	0	1979	1435	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	7	23	23	4 0	6 3	2565
WAYSIDE RADIO	100	6	203	207	3 0	4 4	-640
PHOTO/I-R DETECT	30	6	59	60	3 8	5 9	2190
ULTRASONIC DETECT	20	6	42	43	3 9	6 1	2040

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

SAN DIEGO

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	6	128	95	3 6	5 2	3375
STYLUS MAP	30	6	133	82	3 7	5 1	3285
2-ACCELEROMETERS	34	6	130	99	3 6	5 2	3250
LASER VELOCIMTR	13	7	120	60	3 7	5.2	3175
ULTRASONIC VELO	40	6	131	108	3 5	5 1	3100
COMPASS/ODOMETER	20	6	120	80	3 7	5 2	3340
COMPASS/LASER VEL	15	6	127	79	3 7	5 2	3265
CMPSS/U-SONIC VEL	17	6	128	73	3 7	5 2	3265
OMEGA	1600	0	4004	3928	0 0	0 0	0
LORAN	160	5	401	393	2 0	2 2	1035
DECCA	200	4	483	474	1 5	1 3	510
AM-STATIONS	200	4	481	472	1 5	1 3	535
DIFF OMEGA	160	5	400	393	2.0	2 2	1035
DIFF LORAN	400	2	1109	1095	0 0	0 0	0
DIFF AM-STA	250	4	581	570	1.0	0 2	160
RELAY OMEGA	500	1	10934	6592	0 0	0 0	0
RELAY LORAN	300	0	2272	2221	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	7	126	79	3 7	5 2	3375
REFLECTING SIGNS	10	7	126	79	3 7	5 2	3000
REFLECTING ROAD	3	7	122	76	3 7	5 3	-4770
X-BAND POST	12	7	126	79	3 7	5 2	2355
HF, VHF POST	15	6	126	78	3 7	5 2	3125
LF POST	100	6	265	259	2 7	3 7	1225
LIGHT/I-R POST	30	6	130	81	3 7	5 2	1150
BURIED MAGNETS	4	7	123	77	3 7	5 2	3400
ULTRASONIC POST	20	6	128	80	3 7	5 2	1940
TRAFFIC SENSOR	10	7	126	78	3 7	5 2	3205
CLASS III							
NAR-BAND FM PHASE	1000	0	2550	2494	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3024	2962	0.0	0 0	0
PULSE T-O-ARRIVAL	100	6	191	187	3 1	4 5	2250
NOISE CORRELATION	100	6	214	209	3.0	4 2	2200
DIRECTION FINDER	700	0	1876	1005	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	7	23	23	4 0	6 3	2565
WAYSIDE RADIO	100	6	203	207	3 0	4 4	-640
PHOTO/I-R DETECT	30	6	59	60	3 8	5 9	2190
ULTRASONIC DETECT	20	6	42	43	3 9	6 1	2040

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

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

AREA IS 57.5 SQUARE MILES.

EAST WEST DISTANCE IS 9 MILES.

NORTH SOUTH DISTANCE IS 13 MILES.

TOTAL ROAD MILEAGE IS 1152 MILES.

THE NUMBER OF INTERSECTIONS IS 9570.

THE ESTIMATED NUMBER OF ROAD SEGMENTS IS 19140:

THERE ARE 157 CARS IN THE FLEET.

AND THERE ARE 0 MOTORCYCLES.

THE NUMBER OF VEHICLES ON EACH SHIFT IS:

FIRST SHIFT MAX. 60

FIRST SHIFT MIN. 50

SECOND SHIFT MAX. 90

SECOND SHIFT MIN. 30

THIRD SHIFT MAX. 100

THIRD SHIFT MIN. 30

THE NUMBER OF DISPATCHERS IS 2

THE CITY WOULD REQUIRE 2 WIDE-BAND OR

PULSE ANTENNA SITES AND 14 NARROW BAND

FM ANTENNA SITES FOR 7 AND 3 MILE RADIUS COVERAGE.

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

LA-CENTRAL BUREAU

CLASS I TECHNIQUE	CARS	SITES (THOUSANDS OF $)	BASE	INST	O-M	VOL	SYNC (TOTALS)	RANDOM
KEYBOARD	22	0	72	16	103	237	212	212
STYLUS MAP	401	0	72	16	104	617	592	592
2-ACCELEROMETERS	252	0	100	26	116	513	549	541
LASER VELOCIMTR	280	0	108	32	124	568	599	591
ULTRASONIC VELO	200	0	108	26	124	482	513	505
COMPASS/ODOMETER	231	0	108	14	107	483	521	505
COMPASS/LASER VEL	292	0	109	34	115	573	610	594
CMPSS/U-SONIC VEL	249	0	106	26	115	520	553	542
OMEGA	424	0	92	23	112	676	717	708
LORAN	440	0	92	23	112	692	733	727
DECCA	181	0	92	20	112	429	471	463
AM-STATIONS	63	0	92	18	110	308	338	330
DIFF OMEGA	424	0	92	23	112	676	706	706
DIFF. LORAN	440	0	92	23	112	692	721	727
DIFF. AM-STA.	74	0	92	18	110	318	348	363
RELAY OMEGA	83	0	92	23	116	308	313	376
RELAY LORAN	91	0	92	23	116	346	321	384
CLASS II								
BURIED RES. LOOPS	22	6891	72	11731	103	18843	18858	18812
REFLECTING SIGNS	76	2186	72	1182	295	3755	3770	3730
REFLECTING ROAD	20	230	72	1398	1251	2995	3010	2970
X-BAND POST	27	2202	72	447	246	3017	3032	2992
HF, VHF POST	25	240	72	124	138	623	638	597
LF POST	24	1197	72	448	246	2011	2026	1966
LIGHT/I-R POST	23	957	72	549	344	1969	1984	1944
BURIED MAGNETS	16	690	72	1396	100	2298	2312	2272
ULTRASONIC POST	22	1627	72	1651	296	3691	3706	3666
TRAFFIC SENSOR	23	1819	72	782	102	2822	2837	2797
CLASS III								
NAR-BAND FM PHASE	36	66	142	22	111	376	415	419
WID-BAND FM PHASE	457	24	135	28	205	847	888	890
PULSE T-O-ARRIVAL	405	196	332	69	186	1187	1226	1230
NOISE CORRELATION	124	29	332	31	181	720	734	738
DIRECTION FINDER	6	79	78	17	154	352	333	333
CLASS IV								
TRAFFIC LOOPS	13	9890	72	2616	332	12922	12922	12922
WAYSIDE RADIO	12	8608	72	2180	581	11451	11451	11451
PHOTO\I-R DETECT	19	5497	72	1103	342	7031	7031	7031
ULTRASONIC DETECT	20	5592	72	1102	342	7127	7127	7127

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

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I TECHNIQUE	TOTAL FLEET	SIMPLE SYNC	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	16 85	10 73	11 27	21 80	11 47	12.53	23 60
		5 37	5 63	10 90	5 73	6 27	11 80
STYLUS MAP	17.58	11 20	11 73	22 27	12 40	13 47	24 53
		5 60	5 87	11 13	6 20	6 73	12 27
2-ACCELEROMETERS	17 17	10.93	11 47	22 00	11.87	12 93	24 00
		5 47	5 73	11 00	5 93	6 47	12 00
LASER VELOCIMTR	17 38	11.07	11.60	22.13	12 13	13 20	24 27
		5 53	5 80	11.07	6 07	6 60	12 13
ULTRASONIC VELO	17 17	10 93	11 47	22 00	11 87	12 93	24 00
		5 47	5 73	11.00	5 93	6 47	12 00
COMPASS/ODOMETER	17.17	10 93	11 47	22 00	11 87	12 93	24 00
		5 47	5 73	11 00	5 93	6 47	12 00
COMPASS/LASER VEL	17 17	10 93	11 47	22 00	11 87	12 93	24 00
		5 47	5 73	11 00	5 93	6 47	12 00
CMPSS/U-SONIC VEL	17 17	10 93	11 47	22 00	11 87	12 93	24 00
		5 47	5 73	11 00	5 93	6 47	12 00
OMEGA	18 53	11 80	12 33	22 87	13 60	14 67	25 73
		5 90	6 17	11 43	6 80	7 33	12 87
LORAN	19 05	12 13	12 67	23 20	14 27	15 33	26 40
		6 07	6 33	11.60	7 13	7 67	13 20
DECCA	18 84	12 00	12 53	23 07	14 00	15 07	26 13
		6 00	6 27	11 53	7 00	7 53	13 07
AM-STATIONS	16 96	10 80	11 33	21 87	11 60	12 67	23 73
		5 40	5 67	10 93	5 80	6 33	11 87
DIFF OMEGA	18 53	11 80	12 33	22 87	13 60	14 67	25 73
		5 90	6 17	11 43	6 80	7 33	12 87
DIFF LORAN	19 05	12 13	12 67	23 20	14 27	15 33	26 40
		6 07	6 33	11 60	7 13	7 67	13 20
DIFF AM-STA	18 42	11 73	12 27	22 80	13 47	14 53	25 60
		5 87	6 13	11 40	6 73	7 27	12 80
RELAY OMEGA	1585 70	1010 00	1010 53	1021 07	2010 00	2011 07	2022 13
		505 00	505 27	510 53	1005 00	1005 53	1011 07
RELAY LORAN	68 03	43 33	43 87	54 40	76.67	77 73	88 80
		21 67	21 93	27 20	38 33	38 87	44 40
CLASS II							
BURIED RES LOOPS	17 27	11 00	11 53	22 07	12 00	13 07	24 13
		5 50	5 77	11.03	6 00	6 53	12 07
REFLECTING SIGNS	17 27	11 00	11 53	22 07	12 00	13 07	24 13
		5 50	5 77	11 03	6 00	6 53	12 07
REFLECTING ROAD	17 27	11 00	11 53	22 07	12 00	13 07	24 13
		5 50	5 77	11 03	6 00	6 53	12 07
X-BAND POST	17 17	10 93	11.47	22 00	11 87	12 93	24 00
		5 47	5 73	11 00	5 93	6 47	12 00
HF, VHF POST	16 96	10 80	11.33	21 87	11 60	12 67	23 73
		5 40	5 67	10 93	5 80	6 33	11 87
LF POST	17 17	10 93	11 47	22 00	11 87	12 93	24 00
		5 47	5 73	11 00	5 93	6 47	12 00
LIGHT/I-R POST	17.17	10 93	11 47	22 00	11 87	12 93	24 00
		5 47	5 73	11 00	5 93	6 47	12 00
BURIED MAGNETS	17.27	11 00	11 53	22 07	12 00	13 07	24.13
		5 50	5 77	11 03	6 00	6 53	12 07
ULTRASONIC POST	17.17	10 93	11 47	22 00	11.87	12 93	24 00
		5 47	5 73	11 00	5 93	6 47	12 00
TRAFFIC SENSOR	17 17	10.93	11 47	22.00	11.87	12 93	24 00
		5 47	5 73	11 00	5 93	6 47	12 00

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Table 2-29. Los Angeles, CA, Central Bureau AVM Accuracies and Cost Benefits with One Radio Channel

LA-CENTRAL BUREAU

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	6	396	201	1 4	0 0	535
STYLUS MAP	30	6	410	209	1 3	0 0	455
2-ACCELEROMETERS	34	6	403	205	1 4	0 0	470
LASER VELOCIMTR	13	7	396	201	1.4	0 0	430
ULTRASONIC VELO	40	6	405	206	1 4	0 0	430
COMPASS/ODOMETER	20	6	397	202	1.4	0 0	515
COMPASS/LASER VEL	15	7	394	200	1 4	0 0	475
CMPSS/U-SONIC VEL	17	7	395	201	1 4	0 0	475
OMEGA	1600	0	4199	4079	0 0	0 0	0
LORAN	160	2	460	408	0 0	0 0	0
DECCA	200	1	506	492	0 0	0 0	0
AM-STATIONS	200	1	504	490	0 0	0 0	0
DIFF OMEGA	160	2	449	408	0 0	0 0	0
DIFF LORAN	400	0	1169	1132	0 0	0 0	0
DIFF AM-STA	250	1	616	592	0 0	0 0	0
RELAY OMEGA	500	0	34669	17461	0 0	0 0	0
RELAY LORAN	300	0	2148	2022	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	7	391	199	1 4	0 0	-535
REFLECTING SIGNS	10	7	391	199	1 4	0 0	-425
REFLECTING ROAD	3	7	378	192	1 5	0 0	-5130
X-BAND POST	12	7	391	199	1 4	0 0	-130
HF, VHF POST	15	7	390	198	1 4	0 0	360
LF POST	100	4	415	271	0 7	0 0	-705
LIGHT/I-R POST	30	6	401	204	1 4	0 0	-670
BURIED MAGNETS	4	7	381	193	1 5	0 0	625
ULTRASONIC POST	20	6	397	202	1 4	0 0	-430
TRAFFIC SENSOR	10	7	389	198	1 4	0 0	540
CLASS III							
NAR-BAND FM PHASE	1000	0	2696	2607	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3173	3083	0.0	0 0	0
PULSE T-O-ARRIVAL	100	4	192	165	1 6	1 4	270
NOISE CORRELATION	100	4	215	207	1 3	0 8	70
DIRECTION FINDER	700	0	1984	1916	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	7	23	23	3 2	6 3	3065
WAYSIDE RADIO	100	4	202	209	1.3	1.1	-1930
PHOTO\I-R DETECT	30	6	59	61	2 8	5 3	2265
ULTRASONIC DETECT	20	6	42	43	3.0	5 7	2565

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

LA-CENTRAL BUREAU

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	6	201	95	2.5	1 2	1360
STYLUS MAP	30	6	209	103	2 4	1 0	1200
2-ACCELEROMETERS	34	6	205	101	2.4	1 1	1220
LASER VELOCIMTR	13	7	201	95	2 5	1 2	1055
ULTRASONIC VELO	40	6	206	109	2.3	1 0	1105
COMPASS/ODOMETER	20	6	202	96	2 5	1 2	1340
COMPASS/LASER VEL	15	7	200	95	2 5	1 2	1300
CMPSS/U-SONIC VEL	17	7	201	95	2 5	1 2	1300
OMEGA	1600	0	4079	3963	0 0	0 0	0
LORAN	160	2	408	397	0 0	0 0	0
DECCA	200	1	492	473	0 0	0 0	0
AM-STATIONS	200	1	490	476	0 0	0 0	0
DIFF OMEGA	160	2	408	396	0 0	0 0	0
DIFF LORAN	400	0	1132	1096	0 0	0 0	0
DIFF. AM-STA	250	1	532	575	0 0	0 0	0
RELAY OMEGA	500	0	17461	7973	0 0	0 0	0
RELAY LORAN	300	0	2322	2245	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	7	199	94	2 5	1 3	1360
REFLECTING SIGNS	10	7	199	94	2 5	1 3	400
REFLECTING ROAD	3	7	192	92	2 5	1 5	-4390
X-BAND POST	12	7	199	94	2 5	1 3	645
HF, VHF POST	15	7	198	94	2 5	1 3	1155
LF POST	100	4	271	262	0 3	0 0	-630
LIGHT/I-R POST	30	6	204	101	2 4	1 1	30
BURIED MAGNETS	4	7	193	92	2.5	1 4	1375
ULTRASONIC POST	20	6	202	96	2 5	1 2	395
TRAFFIC SENSOR	10	7	198	94	2.5	1 3	1365
CLASS III							
NAR-BAND FM PHASE	1000	0	2607	2521	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3083	2994	0 0	0 0	0
PULSE T-O-ARRIVAL	100	4	192	185	1 6	1 4	270
NOISE CORRELATION	100	4	215	207	1 3	0 6	70
DIRECTION FINDER	700	0	1918	1855	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	7	23	23	3 2	6 3	3065
WAYSIDE RADIO	100	4	202	209	1.3	1 1	-1930
PHOTO/I-R DETECT	30	6	59	61	2 8	5 3	2265
ULTRASONIC DETECT	20	6	42	43	3 0	5 7	2565

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

LA-CENTRAL BUREAU

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	6	134	93	2.5	3 1	1810
STYLUS MAP	30	6	139	82	2.6	3 0	1730
2-ACCELEROMETERS	34	6	136	97	2 5	3 0	1670
LASER VELOCIMTR	13	7	134	68	2 8	3 1	1705
ULTRASONIC VELO	40	6	137	107	2 4	3 0	1650
COMPASS/ODOMETER	20	6	134	68	2 8	3 1	1790
COMPASS/LASER VEL	15	7	133	67	2 8	3 1	1750
CMPSS/U-SONIC VEL	17	7	133	67	2 8	3 1	1750
OMEGA	1600	0	4011	3896	0 0	0 0	0
LORAN	160	2	401	390	0 0	0 0	0
DECCA	200	1	494	470	0 0	0 0	0
AM-STATIONS	200	1	482	468	0 0	0 0	0
DIFF OMEGA	160	2	401	390	0 0	0 0	0
DIFF LORAN	400	0	1111	1076	0 0	0 0	0
DIFF AM-STA	250	1	582	566	0 0	0 0	0
RELAY OMEGA	500	0	11529	5606	0 0	0 0	0
RELAY LORAN	300	0	2277	2202	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	7	132	67	2 8	3 2	1605
REFLECTING SIGNS	10	7	132	67	2 9	3 2	925
REFLECTING ROAD	3	7	127	65	2 8	3 3	-3700
X-BAND POST	12	7	132	67	2 8	3 2	1170
HF, VHF POST	15	7	131	67	2 8	3 2	1710
LF POST	100	4	265	257	0.3	0 0	-630
LIGHT/I-R POST	30	6	136	82	2 6	3 1	605
BURIED MAGNETS	4	7	128	65	2 8	3 3	1975
ULTRASONIC POST	20	6	134	68	2 [illegible]	3 1	345
TRAFFIC SENSOR	10	7	131	66	2 8	3 2	1690
CLASS III							
NAR-BAND FM PHASE	1000	0	2556	2472	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3031	2935	0 0	0 0	0
PULSE T-O-ARRIVAL	100	4	192	185	1 6	1 4	270
NOISE CORRELATION	100	4	215	207	1 3	0 8	70
DIRECTION FINDER	700	0	1881	1818	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	7	23	23	3 2	6 3	3065
WAYSIDE RADIO	100	4	202	209	1 3	1 1	-1930
PHOTO/I-R DETECT	30	6	59	61	2 8	5 3	2265
ULTRASONIC DETECT	20	6	42	43	3 0	5 7	2565

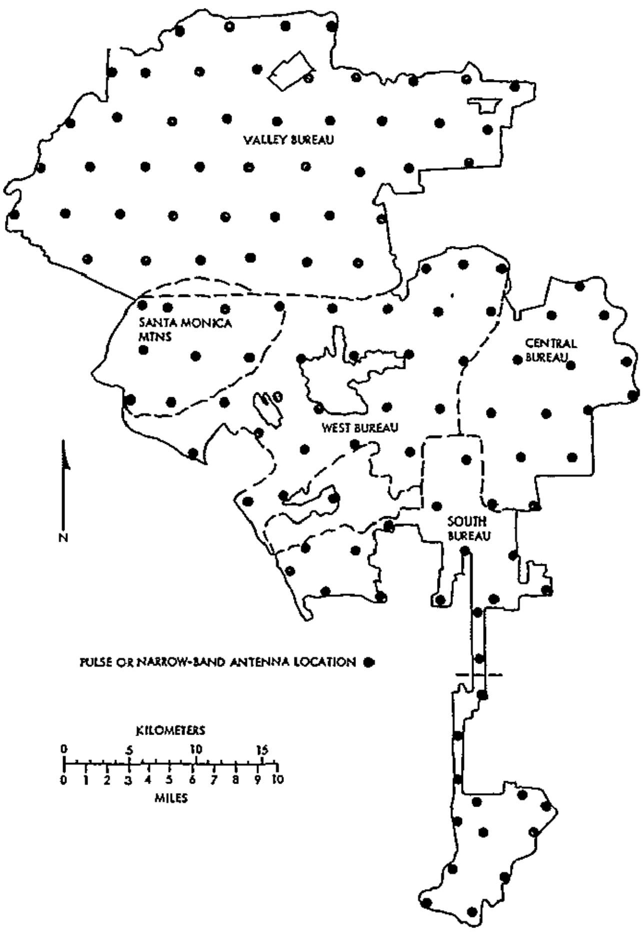


Figure 2-13. Los Angeles, CA, AVM Pulse or Narrow-Band Antennas

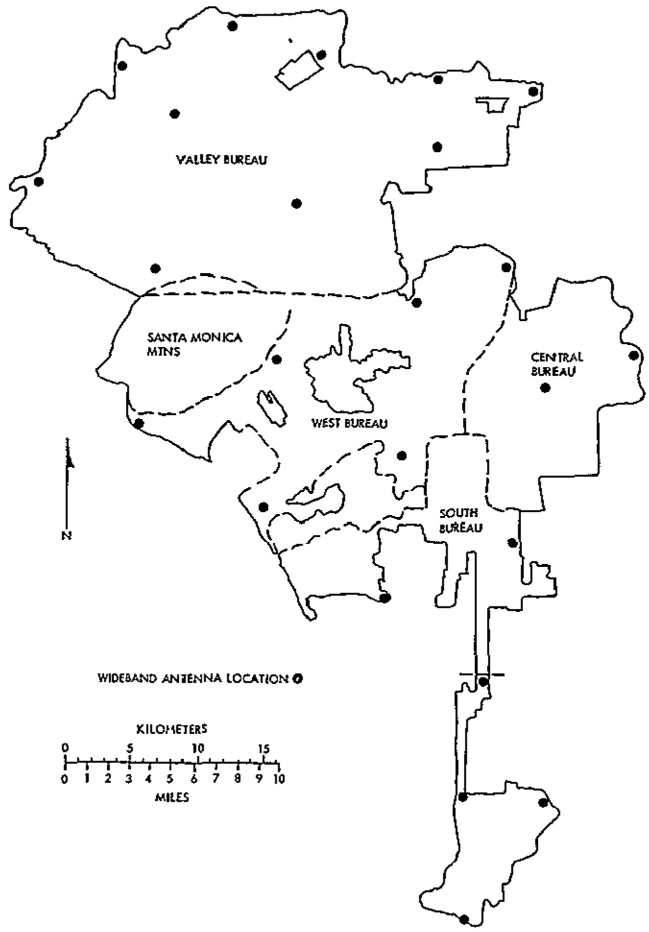


Figure 2-14. Los Angeles, CA, AVM Wide-Band Antenna Locations

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

AREA IS 55.2 SQUARE MILES.

EAST WEST DISTANCE IS 9 MILES.

NORTH SOUTH DISTANCE IS 23 MILES.

TOTAL ROAD MILEAGE IS 973 MILES.

THE NUMBER OF INTERSECTIONS IS 6090.

THE ESTIMATED NUMBER OF ROAD SEGMENTS IS 12190:

THERE ARE 165 CARS IN THE FLEET.

AND THERE ARE 0 MOTORCYCLES.

THE NUMBER OF VEHICLES ON EACH SHIFT IS:

FIRST SHIFT MAX. 63

FIRST SHIFT MIN. 53

SECOND SHIFT MAX. 94

SECOND SHIFT MIN. 64

THIRD SHIFT MAX. 104

THIRD SHIFT MIN. 94

THE NUMBER OF DISPATCHERS IS 2

THE CITY WOULD REQUIRE 5 WIDE-BAND OR

PULSE ANTENNA SITES AND 23 NARROW BAND

FM ANTENNA SITES FOR 7 AND 3 MILE RADIUS COVERAGE.

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

LA-SOUTH BUREAU

CLASS I		THOUSANDS OF $					TOTALS	
TECHNIQUE	CARS	SITES	BASE	INST	O-M	VOL	SYNC	RANDOM
KEYBOARD	23	0	73	16	103	240	214	214
STYLUS MAP	421	0	73	16	105	641	614	614
2-ACCELEROMETERS	264	0	100	27	117	504	566	558
LASER VELOCIMTR	294	0	109	33	125	507	619	611
ULTRASONIC VELO	210	0	109	27	125	497	529	521
COMPASS/ODOMETER	242	0	109	14	107	498	537	520
COMPASS/LASER VEL	307	0	109	35	115	592	631	614
CMPSS/U-SONIC VEL	262	0	107	27	115	507	576	559
OMEGA	446	0	93	24	113	701	745	734
LORAN	462	0	93	24	113	717	761	754
DECCA	190	0	93	20	113	442	486	477
AM-STATIONS	66	0	93	19	110	214	345	338
DIFF. OMEGA	446	0	93	24	113	701	732	734
DIFF LORAN	462	0	93	24	113	717	749	754
DIFF. AM-STA	77	0	93	19	110	325	356	373
RELAY OMEGA	97	0	93	24	117	346	320	336
RELAY LORAN	95	0	93	24	117	354	328	394
CLASS II								
BURIED RES LOOPS	24	4093	73	6975	103	11293	11308	11266
REFLECTING SIGNS	80	1340	73	766	226	2510	2525	2483
REFLECTING ROAD	21	147	73	897	834	1997	2012	1970
X-BAND POST	29	1401	73	291	193	2012	2028	1986
HF, VHF POST	26	153	73	86	125	487	503	461
LF POST	25	762	73	292	194	1371	1387	1345
LIGHT/I-R POST	24	609	73	358	257	1347	1362	1320
BURIED MAGNETS	17	410	73	536	100	1462	1477	1435
ULTRASONIC POST	23	1036	73	1060	226	2443	2458	2416
TRAFFIC SENSOR	24	1158	73	504	102	1886	1902	1860
CLASS III								
NAR-BAND FM PHASE	36	109	143	27	116	431	472	476
WID-BAND FM PHASE	480	58	134	33	207	911	954	956
PULSE T-O-ARRIVAL	425	322	331	93	191	1361	1402	1407
NOISE CORRELATION	130	29	331	31	181	726	742	747
DIRECTION FINDER	6	79	78	17	154	353	334	334
CLASS IV								
TRAFFIC LOOPS	14	4823	73	1673	248	6829	6829	6829
WAYSIDE RADIO	13	4135	73	1393	407	6019	6019	6019
PHOTO\I-R DETECT	19	2548	73	710	255	3605	3605	3605
ULTRASONIC DETECT	21	2609	73	709	255	3667	3667	3667

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

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I	TOTAL		SIMPLE			REDUNDANT	
TECHNIQUE	FLEET	SYNC	VOL	RAND	SYNC	VOL	RAND
KEYBOARD	17-71	11-16	11 72	22 67	11-93	13-04	24-54
		5 69	5 97	11 55	6-08	6-64	12-51
STYLUS MAP	18 48	11-65	12 20	23 16	12-90	14-01	25-51
		5 94	6 22	11 80	6 57	7-14	13-00
2-ACCELEROMETERS	18 04	11-37	11 93	22 88	12-34	13-45	24-96
		5 79	6 08	11 66	6-29	6-85	12-72
LASER VELOCIMTR	18-26	11-51	12 06	23 02	12-62	13-73	25-24
		5 87	6 15	11-73	6 43	7 00	12-86
ULTRASONIC VELO	18-04	11-37	11-93	22 88	12-34	13-45	24 96
		5 79	6 08	11 66	6 29	6 85	12 72
COMPASS/ODOMETER	18-04	11-37	11 93	22 88	12-34	13-45	24-96
		5 79	6 08	11 66	6 29	6 85	12-72
COMPASS/LASER VEL	18-04	11-37	11 93	22 88	12-34	13 45	24-96
		5 79	6 08	11-66	6 29	6 85	12 72
CMPSS/U-SONIC VEL	18-04	11-37	11 93	22-88	12 34	13 45	24-96
		5 79	6 08	11-66	6 29	6 85	12 72
OMEGA	19-47	12 27	12 83	23 78	14 14	15 25	26-76
		6 25	6 54	12-12	7 21	7-77	13 64
LORAN	20 02	12 62	13 17	24 13	14 84	15-95	27 46
		6 43	6 71	12-30	7 56	8-13	13-99
DECCA	19 80	12 48	13 04	23 99	14 56	15 67	27 18
		6-36	6 64	12-23	7 42	7 99	13 85
AM-STATIONS	17-82	11-23	11 79	22-74	12 06	13 17	24 68
		5 72	6 01	11-59	6 15	6-71	12 58
DIFF OMEGA	19-47	12-27	12-83	23 78	14 14	15 25	26 76
		6-25	6 54	12-12	7 21	7-77	13 64
DIFF LORAN	20 02	12-62	13 17	24-13	14 84	15 95	27 46
		6 43	6 71	12-30	7 56	8 13	13-99
DIFF. AM-STA	19 36	12 20	12-76	23-71	14 01	15 12	26 62
		6 22	6-50	12 08	7-14	7 70	13 57
RELAY OMEGA	1666 50	1050 40	1050-95	1061 91	2090 40	2091 51	2103 02
		535 30	535 58	541 17	1065 30	1065 87	1071 73
RELAY LORAN	71 50	45 07	45 62	56 58	79 73	80 84	92 35
		22 97	23 25	28 83	40 63	41 20	47 06
CLASS II							
BURIED RES LOOPS	18 04	11 37	11 93	22 88	12-34	13 45	24 96
		5 79	6 08	11 66	6-29	6 85	12 72
REFLECTING SIGNS	18 04	11 37	11 93	22 88	12 34	13 45	24 96
		5 79	6 08	11 66	6-29	6 85	12-72
REFLECTING ROAD	18 04	11 37	11 93	22 88	12 34	13 45	24 96
		5 79	6 08	11 66	6 29	6 85	12-72
X-BAND POST	17 93	11 30	11 86	22 81	12 20	13-31	24 82
		5 76	6 04	11-63	6 22	6-78	12-65
HF, VHF POST	17-71	11-16	11 72	22-67	11 93	13 04	24 54
		5 69	5 97	11-55	6 08	6-64	12-51
LF POST	17-93	11-30	11-86	22 81	12 20	13 31	24 82
		5 76	6 04	11-63	6 22	6-78	12 65
LIGHT/I-R POST	17-93	11-30	11 86	22-81	12 20	13 31	24-82
		5 76	6 04	11-63	6 22	6-78	12-65
BURIED MAGNETS	18-04	11-37	11-93	22-88	12 34	13 45	24 96
		5 79	6 08	11 66	6 29	6 85	12 72
ULTRASONIC POST	17 93	11-30	11-86	22 81	12 20	13 31	24 82
		5 76	6 04	11 63	6 22	6 78	12 65
TRAFFIC SENSOR	17 93	11-30	11-86	22 81	12 20	13 31	24 82
		5 76	6 04	11 63	6 22	6 78	12 65

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

LA-SOUTH BUREAU

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I	ULTIMATE	THEO VEHICLES	SYSTEM ACCURACY		VEHICLES SAVED		ESTIMATED 5-YEAR
TECHNIQUE	ACCURACY	SAVED	MAX	MIN	MAX	MIN	SAVING
KEYBOARD	33	6	411	213	1 2	0 0	305
STYLUS MAP	30	6	425	221	1 2	0 0	375
2-ACCELEROMETERS	34	6	418	217	1 2	0 0	315
LASER VELOCIMTR	15	7	411	213	1 2	0 0	275
ULTRASONIC VELO	40	6	420	213	1 2	0 0	275
COMPASS/ODOMETER	20	7	412	214	1 2	0 0	365
COMPASS/LASER VEL	15	7	409	212	1 3	0 0	400
CMPSS/U-SONIC VEL	17	7	410	213	1 3	0 0	400
OMEGA	1600	0	4206	4089	0 0	0 0	0
LORAN	160	2	470	469	0 0	0 0	0
DECCA	200	1	507	493	0 0	0 0	0
AM-STATIONS	200	1	505	491	0 0	0 0	0
DIFF OMEGA	160	2	466	409	0 0	0-0	0
DIFF LORAN	400	0	1171	1135	0 0	0 0	0
DIFF AM-STA	250	1	618	594	0 0	0 0	0
RELAY OMEGA	500	0	35972	18512	0 0	0 0	0
RELAY LORAN	300	0	2152	2329	0-0	0 0	0
CLASS II							
BURIED RES LOOPS	10	7	404	209	1 3	0 0	-460
REFLECTING SIGNS	10	7	404	209	1 3	0 0	-155
REFLECTING ROAD	3	7	390	202	1 4	0 0	-3120
X-BAND POST	12	7	404	209	1 3	0 0	10
HF, VHF POST	15	7	402	206	1 3	0 0	350
LF POST	100	4	429	271	0 6	0 0	-520
LIGHT/I-R POST	30	6	414	215	1 2	0 0	-365
BURIED MAGNETS	4	7	394	204	1 4	0 0	550
ULTRASONIC POST	20	7	410	213	1 3	0 0	-155
TRAFFIC SENSOR	10	7	402	208	1 3	0 0	465
CLASS III							
NAR-BAND FM PHASE	1000	0	2702	2615	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3179	3090	0 0	0 0	0
PULSE T-O-ARRIVAL	100	4	192	186	1 6	1 3	2-5
NOISE CORRELATION	100	4	215	208	1 3	0 6	-0
DIRECTION FINDER	700	0	1987	1923	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	7	23	23	3 4	6-5	-3635
WAYSIDE RADIO	100	4	202	209	1 3	1 0	-1060
PHOTO\I-R DETECT	30	6	59	61	3 0	5 4	-2775
ULTRASONIC DETECT	20	7	42	43	3 2	5 9	-3150

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

LA-SOUTH BUREAU

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	6	209	105	2 5	0 7	1360
STYLUS MAP	30	6	217	109	2.4	0 5	1275
2-ACCELEROMETERS	34	6	213	107	2 4	0 6	1215
LASER VELOCIMTR	13	7	209	105	2.5	0.7	1250
ULTRASONIC VELO	40	6	214	108	2.4	0.6	1175
COMPASS/ODOMETER	20	7	210	106	2.5	0 7	1340
COMPASS/LASER VEL	15	7	208	105	2.5	0 8	1300
CMPSS/U-SONIC VEL	17	7	209	105	2 5	0 7	1300
OMEGA	1600	0	4006	3972	0 0	0.0	0
LORAN	160	2	409	398	0 0	0 0	0
DECCA	200	1	493	479	0 0	0 0	0
AM-STATIONS	200	1	491	477	0 0	0 0	0
DIFF. OMEGA	160	2	409	397	0 0	0 0	0
DIFF. LORAN	400	0	1134	1099	0 0	0 0	0
DIFF. AM-STA	250	1	593	577	0 0	0 0	0
RELAY OMEGA	500	0	18162	8380	0 0	0 0	0
RELAY LORAN	800	0	2327	2252	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	7	205	103	2.5	0.9	1360
REFLECTING SIGNS	10	7	205	103	2 5	0 9	745
REFLECTING ROAD	3	7	198	96	2 6	1 1	-2220
X-BAND POST	12	7	205	103	2 5	0 9	910
HF, VHF POST	15	7	205	103	2 5	0 9	1250
LF POST	100	4	271	262	0 7	0 0	-445
LIGHT/I-R POST	30	6	211	106	2 5	0 7	590
BURIED MAGNETS	4	7	200	100	2 5	1 0	1375
ULTRASONIC POST	20	7	209	105	2 5	0 8	745
TRAFFIC SENSOR	10	7	204	103	2 5	0 9	1365
CLASS III							
NAR-BAND FM PHASE	1000	0	2612	2523	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3088	3002	0 0	0 0	0
PULSE T-O-ARRIVAL	100	4	192	186	1 6	1 3	245
NOISE CORRELATION	100	4	215	208	1 3	0 6	-70
DIRECTION FINDER	700	0	1922	1860	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	7	23	23	3.4	6 5	-3635
WAYSIDE RADIO	100	4	202	209	1 3	1.0	-1060
PHOTO\I-R DETECT	30	6	59	61	3.0	5 4	2775
ULTRASONIC DETECT	20	7	42	43	3.2	5 9	3150

Table 2-37. Los Angeles, South Bureau
AVM Accuracies and Cost Benefits
with Three Radio Channels

LA-SOUTH BUREAU

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	6	139	94	2 6	2 9	1660
STYLUS MAP	30	6	144	82	2 7	2 7	1500
2-ACCELEROMETERS	34	6	142	98	2 6	2 8	1515
LASER VELOCIMTR	13	7	139	71	2 9	2 9	1550
ULTRASONIC VELO	40	6	142	107	2.4	2 8	1475
COMPASS/ODOMETER	20	7	139	71	2 9	2 9	1640
COMPASS/LASER VEL	15	7	138	71	2 9	2 9	1600
CMPSS/U-SONIC VEL	17	7	139	71	2 9	2 9	1600
OMEGA	1600	0	4017	3906	0 0	0 0	0
LORAN	160	2	402	391	0 0	0 0	0
DECCA	200	1	484	471	0 0	0 0	0
AM-STATIONS	200	1	482	469	0 0	0 0	0
DIFF. OMEGA	160	2	402	391	0 0	0 0	0
DIFF LORAN	400	0	1113	1079	0 0	0 0	0
DIFF AM-STA	250	1	583	567	0 0	0 0	0
RELAY OMEGA	500	0	12007	5922	0 0	0 0	0
RELAY LORAN	800	0	2281	2208	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	7	136	70	2 9	3 0	1735
REFLECTING SIGNS	10	7	136	70	2 9	3 0	1120
REFLECTING ROAD	3	7	131	68	2 9	3 2	-1770
X-BAND POST	12	7	136	70	2.9	3 0	1205
HF, VHF POST	15	7	136	70	2 9	3 0	1625
LF POST	100	4	266	257	0 3	0 0	-370
LIGHT/I-R POST	30	6	140	82	2 7	2 9	890
BURIED MAGNETS	4	7	133	68	2 9	3 1	1025
ULTRASONIC POST	20	7	139	71	2 9	2 9	1045
TRAFFIC SENSOR	10	7	136	70	2 9	3 0	1740
CLASS III							
NAR-BAND FM PHASE	1000	0	2561	2479	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3036	2944	0 0	0 0	0
PULSE T-O-ARRIVAL	100	4	192	186	1 6	1 3	245
NOISE CORRELATION	100	4	215	208	1 3	0 6	70
DIRECTION FINDER	700	0	1884	1824	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	7	23	23	3 4	6 5	-3635
WAYSIDE RADIO	100	4	202	209	1.3	1 0	-1060
PHOTO\I-R DETECT	30	6	59	61	3 0	5.4	2775
ULTRASONIC DETECT	20	7	42	43	3 2	5 9	3150

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

AREA IS 133.3 SQUARE MILES.

EAST WEST DISTANCE IS 19 MILES.

NORTH SOUTH DISTANCE IS 13 MILES.

TOTAL ROAD MILEAGE IS 1677 MILES.

THE NUMBER OF INTERSECTIONS IS 3400.

THE ESTIMATED NUMBER OF ROAD SEGMENTS IS 16300:

THERE ARE 193 CARS IN THE FLEET.

AND THERE ARE 0 MOTORCYCLES.

THE NUMBER OF VEHICLES ON EACH SHIFT IS:

FIRST SHIFT MAX. 59

FIRST SHIFT MIN. 39

SECOND SHIFT MAX. 105

SECOND SHIFT MIN. 94

THIRD SHIFT MAX. 117

THIRD SHIFT MIN. 95

THE NUMBER OF DISPATCHERS IS 2

THE CITY WOULD REQUIRE 7 WIDE-BAND OF

PULSE ANTENNA SITES AND 44 NARROW BAND

FM ANTENNA SITES FOR 7 AND 3 MILE RADIUS COVERAGE.

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

LA-WEST BUREAU

CLASS I TECHNIQUE	CARS	THOUSANDS OF $ SITES	BASE	INST	O-M	TOTALS VOL	SYNC	RANDOM
KEYBOARD	25	0	78	17	103	252	222	222
STYLUS MAP	467	0	78	17	105	695	666	666
2-ACCELEROMETERS	293	0	111	29	119	580	616	607
LASER VELOCIMTR	326	0	116	35	128	634	670	661
ULTRASONIC VELO	233	0	116	29	128	534	570	561
COMPASS/ODOMETER	269	0	116	14	108	535	579	560
COMPASS/LASER VEL	340	0	116	38	117	639	683	664
CMPSS/U-SONIC VEL	291	0	110	29	117	575	619	600
OMEGA	495	0	98	25	114	760	809	797
LORAN	513	0	98	25	114	779	827	819
DECCA	211	0	98	21	114	473	521	512
AM-STATIONS	74	0	98	20	111	331	366	357
DIFF OMEGA	495	0	98	25	114	760	795	797
DIFF. LORAN	513	0	98	25	114	779	813	819
DIFF. AM-STA.	86	0	98	20	111	343	378	396
RELAY OMEGA	97	0	98	25	119	367	338	411
RELAY LORAN	106	0	98	25	119	376	347	420
CLASS II								
BURIED RES LOOPS	26	6768	78	11524	103	18528	18545	18499
REFLECTING SIGNS	88	2068	78	1166	292	3721	3738	3691
REFLECTING ROAD	23	226	78	1375	1231	2962	2979	2932
X-BAND POST	32	2162	78	441	243	2984	3001	2955
HF, VHF POST	29	235	78	124	138	631	649	602
LF POST	28	1175	78	442	244	1995	2013	1966
LIGHT/I-R POST	27	940	78	541	340	1955	1972	1925
BURIED MAGNETS	19	677	78	1372	100	2275	2292	2245
ULTRASONIC POST	25	1598	78	1624	293	3647	3664	3617
TRAFFIC SENSOR	27	1786	78	770	102	2791	2809	2762
CLASS III								
NAR-BAND FM PHASE	42	208	152	38	127	565	610	615
WID-BAND FM PHASE	532	81	154	37	209	1012	1060	1062
PULSE T-O-ARRIVAL	472	616	343	148	202	1780	1825	1330
NOISE CORRELATION	144	29	343	33	182	759	775	780
DIRECTION FINDER	7	80	91	18	154	370	348	348
CLASS IV								
TRAFFIC LOOPS	15	15470	78	2572	328	18462	18462	18462
WAYSIDE RADIO	14	13709	78	2142	572	16514	16514	16514
PHOTO\I-R DETECT	22	9114	78	1086	338	10636	10636	10636
ULTRASONIC DETECT	23	9208	78	1085	338	10731	10731	10731

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

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I TECHNIQUE	TOTAL FLEET	SIMPLE SYNC	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	19 64	12 56	13 18	25 51	13 42	14 66	27 61
		4 19	4 39	8 58	4 47	4 09	9 26
STYLUS MAP	20 50	13 10	13 73	26 05	14 51	15 76	28 70
		4 37	4 58	8 68	4 84	5 25	9 57
2-ACCELEROMETERS	20 01	12 79	13 42	25 74	13 38	15 13	28 08
		4 26	4 47	8 58	4 63	5 04	9 36
LASER VELOCIMTR	20 25	12 95	13 57	25 90	14 20	15 44	28 34
		4 32	4 52	8 63	4 73	5 15	9 46
ULTRASONIC VELO	20 01	12 79	13 42	25 74	13 38	15 13	28 08
		4 26	4 47	8 58	4 63	5 04	9 36
COMPASS/ODOMETER	20 01	12 79	13 42	25 74	13 38	15 13	28 08
		4 26	4 47	8 58	4 63	5 04	9 36
COMPASS/LASER VEL	20 01	12 79	13 42	25 74	13 38	15 13	28 08
		4 26	4 47	8 58	4 63	5 04	9 36
CMPSS/U-SONIC VEL	20 01	12 79	13 42	25 74	13 38	15 13	28 08
		4 26	4 47	8 58	4 63	5 04	9 36
OMEGA	21 59	13 81	14 43	26 75	15 91	17 16	30 11
		4 60	4 81	8 92	5 30	5 72	10 04
LORAN	22 20	14 20	14 62	27 14	16 69	17 94	30 89
		4 73	4 94	9 05	5 56	5 90	10 30
DECCA	21 96	14 44	14 66	26 99	16 38	17 63	30 54
		4 63	4 89	9 00	5 46	5 88	10 19
AM-STATIONS	19 76	12 64	13 26	25 58	13 57	14 82	27 77
		4 21	4 42	8 53	4 52	4 94	9 26
DIFF OMEGA	21 59	13 81	14 43	26 75	15 41	17 16	30 11
		4 60	4 81	8 92	5 30	5 72	10 04
DIFF LORAN	22 20	14 20	14 62	27 14	16 69	17 94	30 89
		4 73	4 94	9 05	5 56	5 98	10 30
DIFF AM-STA	21 47	13 73	14 35	26 68	15 76	17 00	29 45
		4 58	4 78	8 89	5 25	5 67	9 44
RELAY OMEGA	1848 30	1131 70	1162 32	1194 65	2351 70	2352 95	2365 94
		393 90	394 11	398 22	783 94	784 32	788 63
RELAY LORAN	79 30	50 70	51 32	63 65	39 70	94 95	103 96
		16 40	17 11	21 22	29 90	30 32	[illegible]
CLASS II							
BURIED RES LOOPS	20 13	12 87	13 49	25 82	14 04	15 29	28 24
		4 29	4 50	8 61	4 68	5 10	9 41
REFLECTING SIGNS	20 13	12 87	13 49	25 82	14 04	15 29	28 24
		4 29	4 50	8 61	4 68	5 10	9 41
REFLECTING ROAD	20 13	12 87	13 49	25 82	14 04	15 29	28 24
		4 29	4 50	8 61	4 68	5 10	9 41
X-BAND POST	20 01	12 79	13 42	25 74	13 38	15 13	28 08
		4 26	4 47	8 58	4 63	5 04	9 36
HF VHF POST	19 76	12 64	13 26	25 58	13 57	14 82	27 77
		4 21	4 42	8 53	4 52	4 94	9 26
LF POST	20 01	12 79	13 42	25 74	13 38	15 13	28 08
		4 26	4 47	8 58	4 63	5 04	9 36
LIGHT/I-R POST	20 01	12 79	13 42	25 74	13 38	15 13	28 08
		4 26	4 47	8 58	4 63	5 04	9 36
BURIED MAGNETS	20 13	12 87	13 49	25 82	14 04	15 29	28 24
		4 29	4 50	8 61	4 68	5 10	9 41
ULTRASONIC POST	20 01	12 79	13 42	25 74	13 38	15 13	28 08
		4 26	4 47	8 53	4 63	5 04	9 36
TRAFFIC SENSOR	20 01	12 79	13 42	25 74	13 38	15 13	28 08
		4 26	4 47	8 58	4 63	5 04	9 36

Table 2-42. Los Angeles, West Bureau AVM Accuracies and Cost Benefits with Two Radio Channels

LA-WEST BUREAU

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	7	236	94	2.2	2.5	1360
STYLUS MAP	30	7	244	88	2.3	2.3	1280
2-ACCELEROMETERS	34	7	240	98	2.2	2.4	1285
LASER VELOCIMTR	13	8	236	77	2.3	2.5	1235
ULTRASONIC VELO	40	7	241	108	2.2	2.4	1160
COMPASS/ODOMETER	20	8	236	77	2.3	2.5	1335
COMPASS/LASER VEL	15	8	234	77	2.3	2.6	1365
CMPSS/U-SONIC VEL	17	8	235	77	2.3	2.6	1365
OMEGA	1600	0	4186	3922	0.0	0.0	0
LORAN	160	4	411	393	0.9	0.0	105
DECCA	200	3	495	473	0 5	0.0	-195
AM-STATIONS	200	3	493	471	0 5	0 0	-180
DIFF. OMEGA	160	4	411	392	0 9	0 0	105
DIFF. LORAN	400	1	1140	1084	0 0	0 0	0
DIFF. AM-STA	250	2	596	569	0 1	0 0	-480
RELAY OMEGA	500	0	20440	6450	0 0	0 0	0
RELAY LORAN	800	0	2340	2218	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	8	233	76	2.3	2 6	1435
REFLECTING SIGNS	10	8	233	76	2.3	2 6	490
REFLECTING ROAD	3	8	224	74	2.3	2.8	-4055
X-BAND POST	12	8	233	76	2.3	2 6	735
HF, VHF POST	15	8	231	76	2 3	2 6	1260
LF POST	100	6	273	259	1.5	1 7	55
LIGHT/I-R POST	30	7	239	83	2.3	2 5	175
BURIED MAGNETS	4	8	226	75	2.3	2.8	1600
ULTRASONIC POST	20	8	236	77	2.3	2.5	410
TRAFFIC SENSOR	10	8	231	76	2.3	2.6	1440
CLASS III							
NAR-BAND FM PHASE	1000	0	2627	2491	0.0	0.0	0
WID-BAND FM PHASE	1200	0	3103	2958	0.0	0.0	0
PULSE T-O-ARRIVAL	100	6	193	183	1.8	3.5	1615
NOISE CORRELATION	100	6	216	205	1.7	3.0	1340
DIRECTION FINDER	700	0	1933	1832	0.0	0.0	0
CLASS IV							
TRAFFIC LOOPS	10	8	22	24	2.6	7.6	4060
WAYSIDE RADIO	100	6	201	212	1.7	3.4	-310
PHOTO\I-R DETECT	30	7	59	62	2 4	6.7	3335
ULTRASONIC DETECT	20	8	42	44	2.5	7.1	3635

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

LA-WEST BUREAU

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	7	459	157	2 0	0 0	935
STYLUS MAP	30	7	475	163	1.9	0 0	900
2-ACCELEROMETERS	34	7	467	160	1.9	0 0	830
LASER VELOCIMTR	13	8	459	157	2 0	0 0	860
ULTRASONIC VELO	40	7	469	161	1 9	0 0	-85
COMPASS/ODOMETER	20	8	460	157	2 0	0.0	960
COMPASS/LASER VEL	15	8	456	156	2 0	0 0	915
CMPSS/U-SONIC VEL	17	8	458	156	2 0	0 0	915
OMEGA	1600	0	4227	4037	0 0	0 0	0
LORAN	160	4	534	404	0 3	0 0	30
DECCA	200	3	510	487	0 5	0 0	-195
AM-STATIONS	200	3	508	485	0.5	0 0	-130
DIFF OMEGA	160	4	521	404	0.3	0 0	30
DIFF. LORAN	400	1	1177	1119	0 0	0 0	0
DIFF AM-STA	250	2	623	586	0 0	0.0	0
RELAY OMEGA	500	0	40187	13565	0 0	0 0	0
RELAY LORAN	800	0	2164	2294	0 0	0 0	0
CLASS II							
BURIED RES. LOOPS	10	8	454	155	2 0	0 0	985
REFLECTING SIGNS	10	8	454	155	2.0	0 0	40
REFLECTING ROAD	3	8	438	149	2 0	0 0	-4655
X-BAND POST	12	8	454	155	2 0	0 0	235
HF, VHF POST	15	8	452	154	2 0	0 0	-10
LF POST	100	6	481	267	1 5	0.0	-95
LIGHT/I-R POST	30	7	465	159	2 0	0 0	-200
BURIED MAGNETS	4	8	442	151	2 0	0 0	1000
ULTRASONIC POST	20	8	460	157	2 0	0 0	35
TRAFFIC SENSOR	10	8	451	154	2.0	0 0	990
CLASS III							
NAR-BAND FM PHASE	1000	0	2717	2576	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3194	3051	0 0	0.0	0
PULSE T-O-ARRIVAL	100	6	193	183	1 8	3 5	1615
NOISE CORRELATION	100	6	216	205	1.7	3.0	1340
DIRECTION FINDER	700	0	1999	1895	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	8	22	24	2 6	7 6	4060
WAYSIDE RADIO	100	6	201	212	1 7	3 4	-310
PHOTO\I-R DETECT	30	7	59	62	2 4	6.7	3335
ULTRASONIC DETECT	20	8	42	44	2 5	7 1	3635

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

LA-WEST BUREAU

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	7	157	92	2.3	4 4	2785
STYLUS MAP	30	7	163	81	2.3	4 3	2700
2-ACCELEROMETERS	34	7	160	96	2.2	4 3	2630
LASER VELOCIMTR	13	8	157	54	2.4	4.4	2660
ULTRASONIC VELO	40	7	161	106	2 2	4.3	2585
COMPASS/ODOMETER	20	8	157	51	2 4	4.4	2760
COMPASS/LASER VEL	15	8	156	54	2 4	4.4	2715
CMPSS/U-SONIC VEL	17	8	156	54	2 4	4 4	2715
OMEGA	1600	0	4037	3856	0 0	0 0	0
LORAN	160	4	404	336	0 9	0 0	105
DECCA	200	3	487	465	0 6	0 0	-120
AM-STATIONS	200	3	485	463	0 6	0 0	-105
DIFF. OMEGA	160	4	404	386	0 9	0 0	105
DIFF. LORAN	400	1	1119	1063	0 0	0 0	0
DIFF. AM-STA	250	2	586	560	0.1	0 0	-480
RELAY OMEGA	500	0	13565	4437	0.0	0 0	0
RELAY LORAN	800	0	2294	2175	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	8	155	53	2 4	4 5	2960
REFLECTING SIGNS	10	8	155	53	2 4	4.5	1915
REFLECTING ROAD	3	8	149	52	2.4	4 6	-2705
X-BAND POST	12	8	155	53	2 4	4 5	2160
HF, VHF POST	15	8	154	53	2 4	4 5	2685
LF POST	100	6	267	254	1 5	1 8	100
LIGHT/I-R POST	30	7	159	80	2 3	4 4	1600
BURIED MAGNETS	4	8	151	52	2.4	4 6	2950
ULTRASONIC POST	20	8	157	51	2.4	4 4	1835
TRAFFIC SENSOR	10	8	154	53	2 4	4 5	2065
CLASS III							
NAR-BAND FM PHASE	1000	0	2576	2442	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3051	2900	0 0	0 0	0
PULSE T-O-ARRIVAL	100	6	193	183	1 8	3 5	1615
NOISE CORRELATION	100	6	216	205	1.7	3.0	1340
DIRECTION FINDER	700	0	1895	1797	0.0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	8	22	24	2.6	7.6	4060
WAYSIDE RADIO	100	6	201	212	1 7	3 4	-310
PHOTO\I-R DETECT	30	7	59	62	2 4	6 7	3335
ULTRASONIC DETECT	20	8	42	44	2 5	7 1	3635

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

AREA IS 215.3 SQUARE MILES.

EAST WEST DISTANCE IS 23 MILES.

NORTH SOUTH DISTANCE IS 13.5 MILES.

TOTAL ROAD MILEAGE IS 2661 MILES.

THE NUMBER OF INTERSECTIONS IS 15000

THE ESTIMATED NUMBER OF ROAD SEGMENTS IS 30000:

THERE ARE 123 CARS IN THE FLEET.

AND THERE ARE 0 MOTORCYCLES.

THE NUMBER OF VEHICLES ON EACH SHIFT IS.

FIRST SHIFT MAX. 72

FIRST SHIFT MIN. 61

SECOND SHIFT MAX. 103

SECOND SHIFT MIN. 96

THIRD SHIFT MAX. 121

THIRD SHIFT MIN. 96

THE NUMBER OF DISPATCHERS IS 2

THE CITY WOULD REQUIRE 10 WIDE-BAND OR PULSE ANTENNA SITES AND 45 NARROW BAND FM ANTENNA SITES FOR 7 AND 3 MILE RADIUS COVERAGE.

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

CYCLE TIME IN SECONDS TO POLL MAX AND MIN UNITS DEPLOYED

CLASS I TECHNIQUE	TOTAL FLEET	SIMPLE SYNC	SIMPLE VOL	SIMPLE RAND	REDUNDANT SYNC	REDUNDANT VOL	REDUNDANT RAND
KEYBOARD	20 29	12 99	13 63	26 38	13 88	15 17	28 56
		6 55	6 87	13 30	7.00	7 65	14 40
STYLUS MAP	21 17	13 55	14 20	26 94	15 00	16 29	29 69
		6 3	7 16	13 58	7 56	8 22	14 97
2-ACCELEROMETERS	20 66	13 23	13 88	26 62	14 36	15 65	29 04
		6 67	7.00	13 42	7 24	7 89	14 64
LASER VELOCIMTR	20 92	13 39	14 04	26 78	14 68	15 97	29 36
		6 75	7 08	13 50	7 40	8 05	14 80
ULTRASONIC VELO	20 66	13 23	13 38	26 62	14 36	15 65	29 04
		6 67	7 00	13 42	7 24	7 89	14 64
COMPASS/ODOMETER	20 66	13 23	13 88	26 62	14 36	15 65	29 04
		6 67	7 00	13 42	7 24	7 39	14 64
COMPASS/LASER VEL	20 66	13 23	13 38	26 62	14 36	15 65	29 04
		6 67	7 00	13 42	7 24	7 89	14 64
CMPSS/U-SONIC VEL	20 66	13 23	13 88	26 62	14 36	15 65	29 04
		6 67	7 00	13 42	7 24	7 89	14 64
OMEGA	22 30	14 28	14 92	27 67	16 46	17 75	31 14
		7 20	7 52	13 95	8 30	8 95	15 70
LORAN	22 93	14 68	15 33	28 07	17 26	18 55	31.94
		7 40	7 73	14 15	8 70	9 35	16 10
DECCA	22 68	14 52	15 17	27 41	16 94	18 23	31 62
		7 32	7 65	14 07	8 54	9.19	15 94
AM-STATIONS	20 41	13 07	13 71	26 46	14 04	15 33	28 72
		6 59	6 91	13 34	7 08	7 73	14 42
DIFF OMEGA	22 30	14 28	14 92	27 67	16 46	17 75	31 14
		7 20	7 52	13 95	8 30	8 95	15 70
DIFF LORAN	22 93	14 68	15 33	28 07	17 26	18 55	31 94
		7 40	7 73	14 15	8 70	9 35	16 10
DIFF AM-STA	22 18	14 20	14 84	27 59	16 29	17 54	30 98
		7 16	7 48	13 91	8 22	8 87	15 62
RELAY OMEGA	1908 90	1222 10	1222 75	1235 49	2432.10	2435 39	2446 78
		616 10	616 40	622 85	1226 10	1226 75	1033 50
RELAY LORAN	81 90	52 43	53 08	65 82	92 77	94 06	107 45
		26 43	26 76	33 18	46 72	47 42	54 17
CLASS II							
BURIED RES LOOPS	20 79	13 31	13 96	26 70	14 52	15 81	29 20
		6 71	7 04	13 46	7 32	7 97	14 72
REFLECTING SIGNS	20 79	13 31	13 96	26 70	14 52	15 81	29 20
		6 71	7 04	13 46	7 32	7 97	14 72
REFLECTING ROAD	20 79	13 31	13 96	26 70	14 52	15 81	29 20
		6 71	7 04	13 46	7 32	7 97	14 72
X-BAND POST	20 66	13 23	13 38	26 62	14 36	15 65	29 04
		6 67	7 00	13 42	7 24	7 89	14 64
HF, VHF POST	20 41	13 07	13 71	26 46	14 04	15 33	28 72
		6 59	6 91	13 34	7 08	7 73	14 49
LF POST	20 66	13 23	13 88	26 62	14 36	15 65	29 04
		6 67	7 00	13 42	7 24	7 89	14 64
LIGHT/I-R POST	20 66	13 23	13 88	26 62	14 36	15 65	29 64
		6 67	7 00	13 42	7 24	7 89	14 64
BURIED MAGNETS	20 79	13 31	13 96	26 70	14 52	15 81	29 20
		6 71	7 04	13 46	7 32	7 97	14 72
ULTRASONIC POST	20 66	13 23	13 88	26 62	14 36	15 65	29 04
		6 67	7 00	13 42	7 24	7 89	14 64
TRAFFIC SENSOR	20 66	13 23	13 88	26 62	14 36	15 65	29 04
		6 67	7 00	13 42	7 24	7 89	14 64

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

LA-VALLEY BUREAU

CLASS I TECHNIQUE	CARS	THOUSANDS OF $ SITES	BASE	INST	O-M	VOL	TOTALS SYNC	RANDOM
KEYBOARD	26	0	00	17	163	256	225	225
STYLUS MAP	402	0	00	17	165	714	684	604
2-ACCELEROMETERS	303	0	116	29	114	597	634	625
LASER VELOCIMTR	307	0	114	36	129	650	637	673
ULTRASONIC VELO	241	0	119	29	129	547	534	575
COMPASS/ODOMETER	277	0	119	14	103	548	593	574
COMPASS/LASER VEL	351	0	119	39	110	656	701	632
CMPSS/U-SONIC VEL	200	0	111	29	110	597	633	613
OMEGA	511	0	100	26	115	700	830	819
LORAN	530	0	100	26	115	779	849	841
DECCA	216	0	100	22	115	404	534	524
AM-STATIONS	76	0	100	20	112	337	373	364
DIFF OMEGA	511	0	100	26	115	700	816	819
DIFF LORAN	530	0	100	26	115	794	835	841
DIFF AM-STA	38	0	100	20	112	349	395	404
RELAY OMEGA	100	0	100	26	119	374	344	419
RELAY LORAN	109	0	100	26	119	333	353	429
CLASS II								
BURIED RES LOOPS	27	10300	80	18379	105	24419	29436	24368
REFLECTING SIGNS	41	3300	80	1809	404	5744	5762	5710
REFLECTING ROAD	24	360	80	2162	1903	4579	4596	4548
X-BAND POST	33	3450	80	693	327	4612	4630	4592
HF, VHF POST	30	375	80	107	159	659	877	629
LF POST	29	1875	80	694	328	3035	3050	3005
LIGHT/I-R POST	28	1500	80	850	480	2967	2985	2937
BURIED MAGNETS	19	1080	80	2179	100	3488	3506	3458
ULTRASONIC POST	26	2550	80	2577	405	5667	5665	5637
TRAFFIC SENSOR	28	2850	60	1218	102	4308	4026	4277
CLASS III								
NAR-BAND FM PHASE	43	212	157	39	128	577	624	629
WID-BAND FM PHASE	550	116	164	43	210	1081	1130	1133
PULSE T-O-ARRIVAL	497	630	349	151	203	1819	1866	1871
NOISE CORRELATION	149	29	349	34	182	771	738	793
DIRECTION FINDER	7	50	90	18	154	378	355	355
CLASS IV								
TRAFFIC LOOPS[a]	16	20633	50	4091	462	25281	25281	25281
WAYSIDE RADIO	15	18176	60	3408	852	22529	22529	22529
PHOTO\I-R DETECT	22	11928	30	1719	478	14225	14225	14225
ULTRASONIC DETECT	24	12078	60	1718	478	14376	14376	14376

Table 2-47. Los Angeles, Valley Bureau AVM Accuracies and Cost Benefits with One Radio Channel

LA-VALLEY BUREAU

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	8	474	246	2 5	0 0	1360
STYLUS MAP	30	8	490	255	2 4	0 0	1275
2-ACCELEROMETERS	34	8	482	250	2 5	0 0	1200
LASER VELOCIMTR	13	8	474	246	2 5	0 0	1230
ULTRASONIC VELO	40	8	454	251	2 4	0 0	1155
COMPASS/ODOMETER	20	8	475	246	2 5	0 0	1335
COMPASS/LASER VEL	15	8	471	244	2 5	0 0	1285
CMPSS/U-SONIC VEL	17	8	473	245	2 5	0 0	1285
OMEGA	1600	0	4233	4113	0 0	0 0	0
LORAN	160	5	551	412	1 3	0 0	400
DECCA	200	3	549	496	0 7	0 0	750
AM-STATIONS	200	5	508	494	0 7	0 0	735
DIFF OMEGA	160	5	538	411	1 3	0 0	400
DIFF LORAN	400	1	1179	1142	0 0	0 0	0
DIFF AM-STA	250	4	624	597	0 0	0 0	0
RELAY OMEGA	500	1	41478	21317	0 0	0 0	0
RELAY LORAN	300	0	2163	2345	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	6	468	243	2 5	0 0	1260
REFLECTING SIGNS	10	8	468	243	2 5	0 0	1145
REFLECTING ROAD	3	8	452	234	2 6	0 0	1565
X-BAND POST	13	8	468	243	2 5	0 0	240
HF, VHF POST	15	3	466	241	2 5	0 0	1600
LF POST	100	6	497	273	2 3	0 0	35
LIGHT/I-R POST	30	8	430	249	2 5	0 0	1525
BURIED MAGNETS	4	8	456	236	2 6	0 0	1450
ULTRASONIC POST	20	8	475	246	2 5	0 0	1150
TRAFFIC SENSOR	10	8	460	241	2 5	0 0	1365
CLASS III							
NAR-BAND FM PHASE	1000	0	2722	2632	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3199	3108	0 0	0 0	0
PULSE T-O-ARRIVAL	100	6	194	187	2 9	4 6	2435
NOISE CORRELATION	100	6	217	209	2 7	4 1	2165
DIRECTION FINDER	700	0	2002	1937	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	3	22	23	4 1	6 0	3690
WAYSIDE RADIO	100	6	200	207	2 8	4 5	7385
PHOTO\I-R DETECT	30	3	56	60	3 2	7 3	3085
ULTRASONIC DETECT	20	3	42	43	3 9	7 6	3310

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

LA-VALLEY BUREAU

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	8	244	122	3.4	3 6	2135
STYLUS MAP	30	8	253	126	3 3	3 4	2025
2-ACCELEROMETERS	34	8	248	124	3 3	3 5	2030
LASER VELOCIMTR	13	8	244	122	3 4	3 6	2055
ULTRASONIC VELO	40	8	249	125	3 3	3.5	1900
COMPASS/ODOMETER	20	8	244	122	3 4	3 6	2160
COMPASS/LASER VEL	15	8	242	121	3 4	3 6	2110
CMPSS/U-SONIC VEL	17	8	243	121	3 4	3 6	2110
OMEGA	1600	0	4112	3996	0 0	0 0	0
LORAN	160	3	412	400	1 4	0 3	475
DECCA	200	5	496	482	0 8	0 0	25
AM-STATIONS	200	5	494	480	0 8	0 0	40
DIFF OMEGA	160	5	411	400	1 4	0 3	475
DIFF LORAN	400	1	1142	1106	0 0	0 0	0
DIFF. AM-STA	250	4	597	580	0 1	0 0	-435
RELAY OMEGA	500	1	21141	10516	0 0	0 0	0
RELAY LORAN	300	0	2344	2267	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	8	241	120	3 4	3 7	2260
REFLECTING SIGNS	10	8	241	120	3 4	3 7	755
REFLECTING ROAD	3	0	232	116	3 4	3 8	-6665
X-BAND POST	12	8	241	120	3 4	3 7	1140
HF, VHF POST	15	8	239	120	3 4	3 7	1930
LF POST	100	6	273	264	2 4	3 0	610
LIGHT/I-R POST	30	8	247	124	3 3	3 5	225
BURIED MAGNETS	4	8	234	117	3 4	3 8	2350
ULTRASONIC POST	20	8	244	122	3 4	3.6	675
TRAFFIC SENSOR	10	8	239	119	3 4	3 7	2265
CLASS III							
NAR-BAND FM PHASE	1000	0	2631	2545	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3107	3020	0.0	0 0	0
PULSE T-O-ARRIVAL	100	6	194	187	2.9	4 6	2435
NOISE CORRELATION	100	6	217	209	2.7	4 1	2165
DIRECTION FINDER	700	0	1936	1873	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	8	22	23	4 1	3 0	3690
WAYSIDE RADIO	100	6	200	207	2 8	4.5	-805
PHOTO\I-R DETECT	30	8	59	60	3 8	7 3	3085
ULTRASONIC DETECT	20	8	42	43	3 9	7 6	3310

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

LA-VALLEY BUREAU

SYSTEM ACCURACIES (M), VEHICLES AND ESTIMATED $1000 SAVINGS

CLASS I TECHNIQUE	ULTIMATE ACCURACY	THEO VEHICLES SAVED	SYSTEM ACCURACY MAX	SYSTEM ACCURACY MIN	VEHICLES SAVED MAX	VEHICLES SAVED MIN	ESTIMATED 5-YEAR SAVING
KEYBOARD	33	8	162	45	3 6	5 2	3305
STYLUS MAP	30	8	168	83	3 6	5 1	3300
2-ACCELEROMETERS	34	8	165	99	3.5	5 2	3305
LASER VELOCIMTR	13	8	162	80	3 7	5 2	3255
ULTRASONIC VELO	40	8	166	108	3 5	5 1	3180
COMPASS/ODOMETER	20	9	163	80	3 7	5 2	3260
COMPASS/LASER VEL	15	8	161	80	3 7	5 2	3310
CMPSS/U-SONIC VEL	17	8	162	80	3 7	5 2	3310
OMEGA	1600	0	4043	3929	0 0	0 0	0
LORAN	160	5	405	393	1 4	0 4	475
DECCA	200	5	488	474	0 9	0 0	100
AM-STATIONS	200	5	406	472	0 9	0 0	115
DIFF. OMEGA	160	5	404	393	1.4	0 4	475
DIFF LORAN	400	1	1121	1086	0 0	0 0	0
DIFF AM-STA	250	4	587	570	0 2	0 0	-110
RELAY OMEGA	500	1	14046	6685	0 0	0 0	0
RELAY LORAN	600	0	2298	2223	0 0	0 0	0
CLASS II							
BURIED RES LOOPS	10	8	160	79	3 7	5 3	3400
REFLECTING SIGNS	10	8	160	79	3 7	5 3	1455
REFLECTING ROAD	3	0	154	77	3 7	5 4	-5465
X-BAND POST	12	8	160	79	3 7	5 3	2340
HF, VHF POST	15	8	159	79	3 7	5 3	3190
LF POST	100	6	208	259	2 4	0 1	605
LIGHT/I-R POST	30	8	165	81	3 6	5 2	1500
BURIED MAGNETS	4	8	156	77	3 7	5 3	3475
ULTRASONIC POST	20	8	163	80	3 7	5 2	1375
TRAFFIC SENSOR	10	8	159	79	3 7	5 3	3465
CLASS III							
NAR-BAND FM PHASE	1000	0	2580	2496	0 0	0 0	0
WID-BAND FM PHASE	1200	0	3055	2964	0.0	0 0	0
PULSE T-O-ARRIVAL	100	6	194	187	2 9	4.6	2435
NOISE CORRELATION	100	6	217	209	2 7	4 1	2165
DIRECTION FINDER	700	0	1898	1836	0 0	0 0	0
CLASS IV							
TRAFFIC LOOPS	10	8	22	23	4 1	8 0	3690
WAYSIDE RADIO	100	6	200	207	2.8	4 5	-805
PHOTO\I-R DETECT	30	8	58	60	3 8	7 3	3085
ULTRASONIC DETECT	20	8	42	43	3 4	7 6	3310

PART THREE:

ANALYTICAL TECHNIQUES FOR ESTIMATING AVM SYSTEM ACCURACY

J.E. Fielding
M. Perlman

CONTENTS

FIGURES

TABLES

Joseph E. Fielding

I. VEHICLE LOCATION ACCURACY FOR CLASS I AND III SYSTEMS

In this Section, an algorithm is 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 probability 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 error, ϵ_o, is defined to be the distance between the vehicle's actual location and the location determined by the AVM system at the instant of polling. Inherent error is assumed to be consistent with a Rayleigh distribution, i. e.,

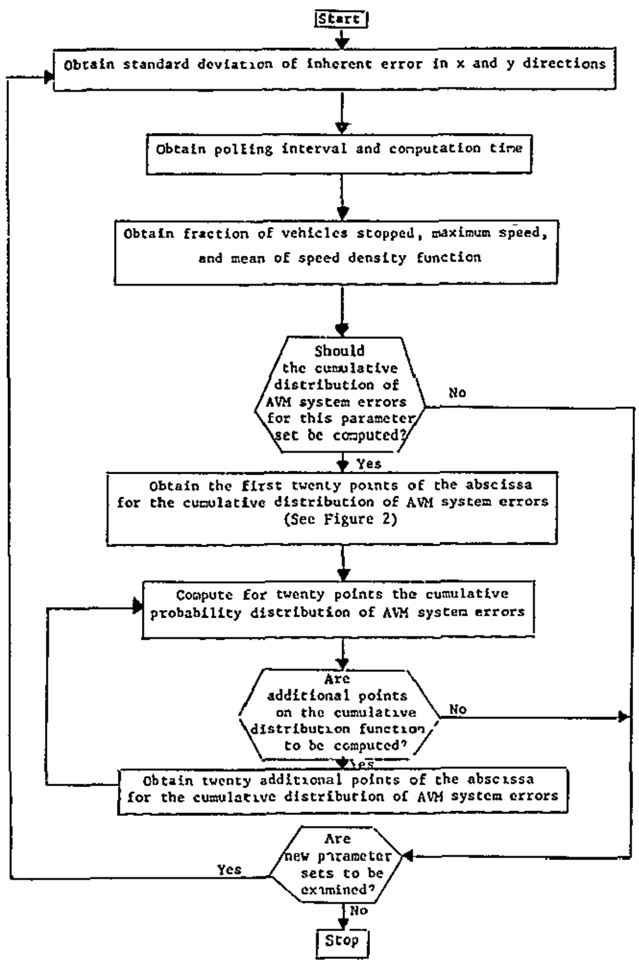


Fig. 3-1. Main AVM Accuracy Analysis Program

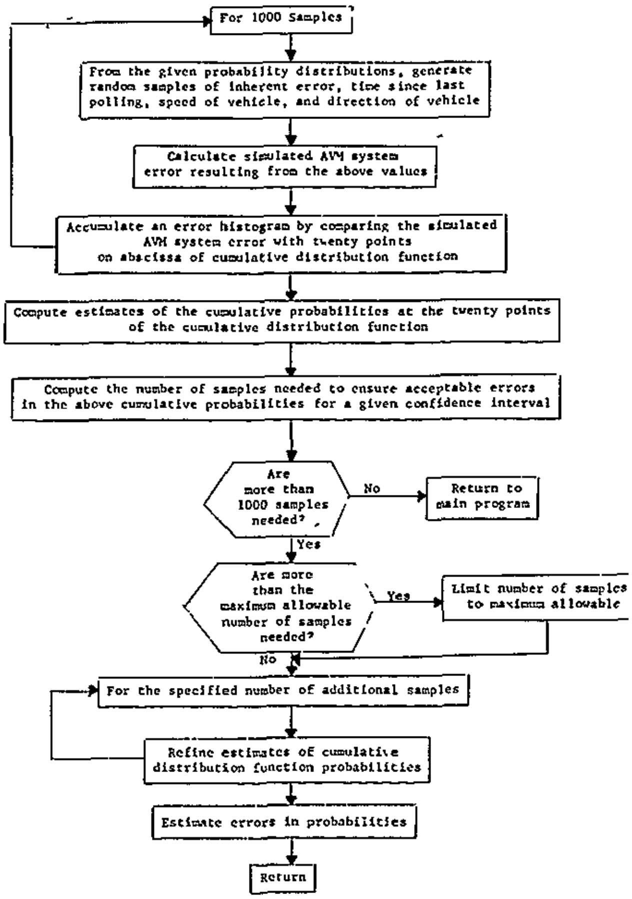


Fig. 3-2. Computation of Cumulative Distribution Function

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

As time passes, the vehicle's location changes by a distance of $(s \cdot t)$ and a direction θ. (See Fig. 3-3.) The random variable θ 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 π.

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

$$f(s) = \begin{cases} FO \cdot \delta & s=0 \\ \lambda e^{-\lambda s} & 0 < s < M \\ 0 & \text{otherwise} \end{cases}$$

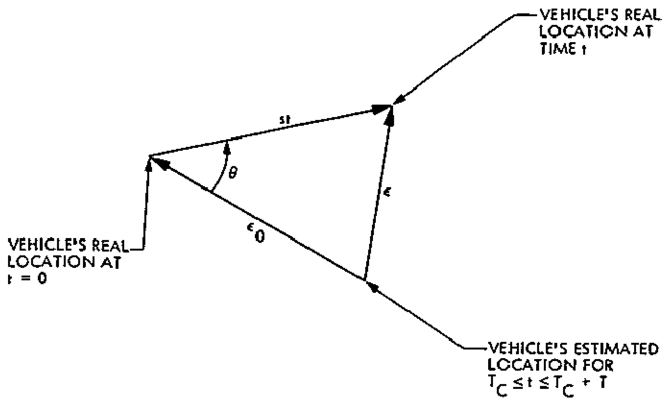


Fig. 3-3. Error in Knowledge of Vehicle's Location

There is a discrete probability FO, associated with zero speed. Between speeds zero 0 and maximum M, the speed is distributed exponentially. The parameter λ 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 is 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, T_C. Thus, if the symbol T denotes the polling interval, the probability density function g(t) is a uniform distribution over the time interval T_C through $T_C + T$.

B. Derivation of Accuracy Analysis Algorithm

Probability distribution functions have been defined for ϵ_0, θ, s, and t, and from Fig 3-3 the actual error in the knowledge of the vehicle's location, ϵ, is:

$$\epsilon = \sqrt{\epsilon_0^2 + s^2 t^2 - 2\epsilon_0 st \cos\theta}$$

The distribution of errors is given by:

$$\text{cdfy} = \text{Prob}(\epsilon \le y) = \iiiint_R \Phi(\epsilon_0)\, g(t) \cdot f(s)\, p(\theta)\, d\theta\, ds\, dt\, d\epsilon_0,$$

where R is the region such that $\epsilon \le y$. 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, ϵ_0, s, t, θ and uses these variables to calculate ϵ by the above formula. By checking whether $\epsilon \le y_i$ for i=1, ..., 20, when the y_i'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 ϵ_0, s, t and θ involves generating four uniform variates on [0, 1] r_1, r_2, r_3, r_4. Inverting the cumulative density functions leads to the expressions needed to calculate the desired variables:

$$\epsilon_0 = \sigma\sqrt{-2 \ln r_1}$$

$$t = T_C + r_2 T$$

$$s = \begin{cases} 0 & 0 \le r_3 \le FO \\ \dfrac{\ln(1-r_3)}{-\lambda} & FO < r_3 \le 1 \end{cases}$$

$$\theta = \pi(2r_4 - 1)$$

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

$$\sigma = \sqrt{n\, p(1-p)}/n$$

where n = number of trials, and p_i has been replaced by p for simplicity.

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

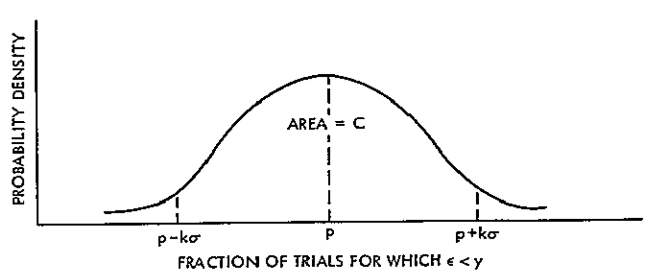


Fig. 3-4. Probability Density vs Fraction of Trials

to ensure an acceptable absolute error, E, it is required that the interval $k\sigma$ be less than or equal to E:

$$k\sigma \le E.$$

Substituting the expression for the standard deviation σ into this last equation gives

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

which may be rewritten

$$n \ge k^2 p(1-p)/E^2$$

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 contained within the interval $p \pm k\sigma$, 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_i is then estimated as

$$(\text{number of times } \epsilon \le y_i)/1000 \text{ for } i=1,\ldots,20.$$

These approximate values of p_i 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_i, 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 until the error terms are sufficiently small or until the maximum 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_i'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" 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 against failure of full coverages, the program allows 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 = Polling interval
- TC = Computation time
- M = Maximum speed
- FO = Fraction stopped

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

SIGMA (meters)	T (seconds)	TC (seconds)	M (meters/sec)	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) might 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 (maximum speed/6) or 22.3 miles/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 balance with respect to inherent accuracy, polling interval, and computation time so as to minimize cost as well as satisfy accuracy constraints.

The best accuracy results are obtained when SIGMA is set equal to zero. With 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 maximum speed or computation time. As the polling interval is increased to to 10 seconds, 80% of the fleet is located to within 65 meters at maximum speed of 40 meters/second and to within 105 meters at 60 meters/second. Thus, as polling interval increases, accuracy becomes more dependent on maximum 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, the dependence on maximum speed increases, and accuracy is not dependent on computation time.

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

T (sec)	TC (sec)	M (meters/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 (sec)	TC (sec)	M (meters/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

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 significantly 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 striking difference 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 accuracies 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 Location Accuracy at 80% Level for SIGMA = 1000 Meters

T (sec)	TC (sec)	M (meters/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	40	2780
300	.1	60	3650

II. MARKOV CHAIN MODEL OF VEHICLE LOCATION BY MEANS OF PROXIMITY SENSORS FOR CLASS II AND IV SYSTEMS

Marvin Perlman

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 is 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 communicating 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. Classifications 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 prediction 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 experiment 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 is characterized by a finite set of states $\{s_1, s_2, \ldots, s_n\}$. 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 probability p_{ij} is the probability that the (Markov chain) process will move from state s_i to s_j, and p_{ij} depends only on s_i. Associated with every ordered pair of states is a known transition probability. An n x n transition probability matrix P contains as entries the transition probabilities corresponding to each of the respective n^2 ordered pairs of states as follows:

$$P = \begin{array}{c} \\ s_1 \\ s_2 \\ \cdot \\ \cdot \\ \cdot \\ s_n \end{array} \begin{array}{c} \begin{array}{cccc} s_1 & s_2 & \cdots & s_n \end{array} \\ \left[\begin{array}{cccc} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{array}\right] \end{array}$$

Each row in P comprises a probability event space such that

$$p_{ij} \geq 0 \qquad \text{for all } i, j$$

and

$$\sum_{j=1}^{n} p_{ij} = 1 \qquad \text{for every } i$$

The transition probability matrix P and an initial (starting state completely describe a finite Markov chain process.

2. Regular Markov chains. A Markov chain is defined to be regular if and only 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 $p_{ij}^{(n)}$ in P^n (the n^{th} power of the transition matrix) is the probability that the process is in state s_j after n steps given that it started in state s_i. A regular Markov chain has a regular transition matrix P such that P^n contains only positive entries (i.e., $p_{ij}^{(n)} > 0$ for all i, j). P may be tested for regularity by noting whether or not the entries in P^2, $(P^2)^2$, $(P^4)^2$, . . . are positive assuming P has one or more 0 entry.

Example 1. Given the following (probability) matrix

$$P = \begin{array}{c} \\ s_1 \\ s_2 \\ s_3 \\ s_4 \end{array} \begin{array}{c} \begin{array}{cccc} s_1 & s_2 & s_3 & s_4 \end{array} \\ \left[\begin{array}{cccc} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0.5 & 0.25 & 0 & 0.25 \\ 0 & 0 & 0.5 & 0.5 \end{array}\right] \end{array}$$

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

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

P^2, P^4 and P^8 are, respectively

$$\begin{bmatrix} 0 & 0 & x & 0 \\ x & x & 0 & x \\ 0 & x & x & x \\ x & x & x & x \end{bmatrix}, \quad \begin{bmatrix} 0 & x & x & x \\ x & x & x & x \\ x & x & x & x \\ x & x & x & x \end{bmatrix} \text{ and } \begin{bmatrix} x & x & x & x \\ x & x & x & x \\ x & x & x & x \\ x & x & x & x \end{bmatrix}$$

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 chain is not necessarily regular. That is, for every n, P^n contains some 0 entries. However, P^n for different values of n, will contain 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 either cyclic or regular but not both.

Example 2. Given the following transition matrix

$$P = \begin{array}{c} \\ s_1 \\ s_2 \\ s_3 \\ s_4 \end{array} \begin{array}{c} \begin{array}{cccc} s_1 & s_2 & s_3 & s_4 \end{array} \\ \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0.25 & 0 & 0.75 & 0 \\ 0 & 0.25 & 0 & 0.75 \\ 0 & 0 & 1 & 0 \end{bmatrix} \end{array}$$

or

$$P = \begin{bmatrix} 0 & x & 0 & 0 \\ x & 0 & x & 0 \\ 0 & x & 0 & x \\ 0 & 0 & x & 0 \end{bmatrix}.$$

where x denotes a positive entry. For even $n > 0$,

$$P^n = \begin{bmatrix} x & 0 & x & 0 \\ 0 & x & 0 & x \\ x & 0 & x & 0 \\ 0 & x & 0 & x \end{bmatrix}$$

For odd $n > 1$,

$$P^n = \begin{bmatrix} 0 & x & 0 & x \\ x & 0 & x & 0 \\ 0 & x & 0 & x \\ x & 0 & x & 0 \end{bmatrix}$$

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 odd-numbered 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 $P_{ii} = 1$ for each s_i that is absorbing.

Example 3. The following transition matrix characterizes an absorbing chain

$$P = \begin{array}{c} \\ s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \end{array} \begin{array}{c} \begin{array}{ccccc} s_1 & s_2 & s_3 & s_4 & s_5 \end{array} \\ \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0.5 & 0 & 0.5 & 0 & 0 \\ 0 & 0.5 & 0 & 0.5 & 0 \\ 0 & 0 & 0.5 & 0 & 0.5 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \end{array}$$

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 chains. Each of the unrelated chains consists of a single ergodic set and may be treated separately. Without any loss in generality, every ergodic chain (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. Properties 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 relabeling states)

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

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

$$p_{ij} = \begin{cases} 0 \text{ if } i \neq j \\ 1 \text{ if } i = j \end{cases}$$

The submatrix Q is an m x m matrix whose entries are the transition probabilities for every ordered pair of transient states. The submatrix R is an $m \times \ell$ matrix whose entries are the transition probabilities for every ordered pair of states (s_i, s_j) where s_i is a transient state and s_j is an absorbing state. The submatrix 0 is an $\ell \times m$ 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

$$M = [I + Q + Q^2 + \cdot\cdot\cdot + Q^{n-1}]R$$

Note that the expression for M is a matrix equation.

Theorem 1. In any finite Markov chain, regardless of the initial (starting) state, the probability that the process is in ergodic state after n steps approaches 1 as n approaches infinity. (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

$$p_{ij}^{(n)} \leq bc^n$$

for any ordered pair of transient states (s_i, s_j). This gives the rate at which $p_{ij}^{(n)}$ 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 is defined as

$$N = [I - Q]^{-1} \tag{1}$$

Note that

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

and since $Q \neq I$ and $\lim_{n\to\infty} Q^n = 0$

$$[I - Q]^{-1} = \lim_{n\to\infty} [I + Q + Q^2 + \cdot\cdot\cdot + Q^{n-1}]$$

the inverse of I - Q (i.e., N) always exists.

The submatrix M in P^n as n approaches infinity may be expressed as

$$M = [I - Q]^{-1} R = NR \tag{2}$$

The fundamental matrix N has the following probabilistic interpretation.

Let $u_{ij}^{(k)} = 1$ if the process starts in transient state s_i and is in transient state s_j after k moves. Otherwise $u_{ij}^{(k)} = 0$. Let $t_{ij}^{(n)}$ denote the number of times the process is in transient state s_j starting and during n moves given that it started in transient state s_i. Thus

$$t_{ij}^{(n)} = u_{ij}^{(0)} + u_{ij}^{(1)} + \cdot\cdot\cdot + u_{ij}^{(n)}$$

The probability that the process is in transient state s_j after the k^{th} move is

$$p(u_{ij}^{(k)} = 1) = q_{ij}^{(k)}$$

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

$$m(u_{ij}^{(k)} = 1 \cdot q_{ij}^{(k)} + 0 \cdot (1 - q_{ij}^{(k)} = q_{ij}^{(k)}$$

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

$$m(t_{ij}^{(n)}) = q_{ij}^{(0)} + q_{ij}^{(1)} + \cdot\cdot\cdot q_{ij}^{(n)}$$

the i,j^{th} entry of

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

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

Then

$$n_{ij} = \lim_{n\to\infty} m(t_{ij}^{(n)})$$

is the i, j^{th} entry of the fundamental matrix expressed in (1). The value of n_{ij} is the mean number of times the chain is in transient state s_j given that it started in transient state s_i and continues until the process is absorbed (i.e., reaches an absorbing state).

3. Statistics on the number of times the process is in a transient state. Let v_i denote the number of steps (including the original position) before absorption, given the starting state is s_i. If s_i is in an absorbing state, then $v_i = 0$. Given that the absorbing chain contains a transient set denoted by T, and s_i is a transient state if and only if $s_i \varepsilon T$ (i.e., s_i "is a member of" T). Then

$$m(v_i) = \sum_{s_j \varepsilon T} n_{ij} \tag{3}$$

which is the i^{th} row sum of the fundamental matrix N. Each row sum of N appears in the m x 1 column vector

$$\alpha = NC \tag{4}$$

where C is a m x 1 column vector whose entries are all 1's.

The variance of the function v_i is

$$\text{var}(v_i) = m(v_i^2) - (m(v_i))^2$$

where

$$m(v_i^2) = \sum_{s_j \not\varepsilon T} p_{ij} \cdot 1 + \sum_{s_j \varepsilon T} p_{ij}\, m\,[(v_i + 1)^2]$$

(Note that the original position is necessarily included in the expression for $m(v_i^2)$.)

Continuing,

$$m(v_i^2) = \sum_{s_j \not\varepsilon T} p_{ij} + \sum_{s_j \varepsilon T} p_{ij}\, m(v_i^2 + 2v_i) + p_{ij}$$

$$= \sum_{s_j \varepsilon T} p_{ij}\, [m(v_i^2) + 2\, m(v_i)] + 1$$

$$\{m(v_i^2)\} = \left\{ \sum_{s_j \varepsilon T} p_{ij}\, [m(v_i^2) + 2\, m(v_i)] + 1 \right\}$$

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

Therefore,

$$\{m(v_i^2)\} = Q\, \{m(v_i^2)\} + 2Q\alpha + C$$

$$[I - Q]\, \{m(v_i^2)\} = 2Q\alpha + C$$

$$\{m(v_i^2)\} = [I - Q]^{-1}\, [2Q\alpha + C]$$

$$= 2NQ\alpha + NC$$

$$= 2NQ\alpha + \alpha$$

Since

$$N = \frac{I}{I - Q}$$

$$N - NQ = I \quad \text{and} \quad NQ = N - I$$

and

$$\{m(v_i^2)\} = 2[N - I]\alpha + \alpha$$

$$= [2N - I]\alpha$$

Finally, the variance of v_i for each i expressed as entries in m x 1 column vector is

$$\{\text{var}(v_i)\} = \{m(v_i^2) - (m(v_i))^2\}$$

$$= [2N - I]\alpha - \alpha_{sq}$$

where α_{sq} results from squaring each entry $m(v_i)$ in α shown in (4).

Example 4. A particle moves a unit distance along a straight line. Given that it is in s_i, it moves to s_{i+1}, one unit to the right, with probability 0.5, or to state s_{i-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 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:

$$P = \begin{array}{c} \\ s_1 \\ s_5 \\ s_2 \\ s_3 \\ s_4 \end{array} \begin{array}{c} \begin{array}{ccccc} s_1 & s_5 & s_2 & s_3 & s_4 \end{array} \\ \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0.5 & 0 & 0 & 0.5 & 0 \\ 0 & 0 & 0.5 & 0 & 0.5 \\ 0 & 0.5 & 0 & 0.5 & 0 \end{bmatrix} \end{array}$$

The fundamental matrix is

$$N = [I - Q]^{-1} = \begin{matrix} & s_2 & s_3 & s_4 \\ s_2 & 1.5 & 1 & 0.5 \\ s_3 & 1 & 2 & 1 \\ s_4 & 0.5 & 1 & 1.5 \end{matrix}$$

Thus, for example, if 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,

$$\lim_{n\to\infty} P^n = \left[\begin{array}{c|c} I & 0 \\ \hline NR & 0 \end{array}\right]$$

since

$$\lim_{n\to\infty} Q^n = 0$$

and

$$\lim_{n\to\infty} M = NR$$

as shown in (1) and (2).

In example 4

$$R = \begin{matrix} & s_1 & s_5 \\ s_2 & 0.5 & 0 \\ s_3 & 0 & 0 \\ s_4 & 0 & 0.5 \end{matrix}$$

and

$$NR = \begin{matrix} & s_1 & s_5 \\ s_2 & 0.75 & 0.25 \\ s_3 & 0.5 & 0.5 \\ s_4 & 0.25 & 0.75 \end{matrix}$$

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 α as shown in (4).

$$\alpha = NC = \begin{matrix} s_2 \\ s_3 \\ s_4 \end{matrix} \begin{bmatrix} 3 \\ 4 \\ 3 \end{bmatrix}$$

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

$$[2N - I]\,\alpha - \alpha_{sq}$$

from expression (5). In example (4)

$$2N - I = \begin{bmatrix} 2 & 2 & 1 \\ 2 & 3 & 2 \\ 1 & 2 & 2 \end{bmatrix}, \quad \alpha = \begin{bmatrix} 3 \\ 4 \\ 3 \end{bmatrix} \text{ and } \alpha_{sq} = \begin{bmatrix} 9 \\ 16 \\ 9 \end{bmatrix}$$

Thus

$$[2N - I]\alpha - \alpha_{sq} = \begin{matrix} s_2 \\ s_3 \\ s_4 \end{matrix} \begin{bmatrix} 8 \\ 8 \\ 8 \end{bmatrix}$$

The mean number of steps before absorption is greatest for starting at s_3. However, the variance is the same for each starting transient state. (Note that when the variances are quite large compared to the corresponding entries in α_{sq}, it indicates that the means are unreliable estimates for that particular chain.)

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

Consider a portion of an area to be monitored as shown in Fig. 3-5. Subareas are 5 x 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 vehicle'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 vehicle is sensed, a new experiment begins. Thus, between sensings, an uncertainty 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.

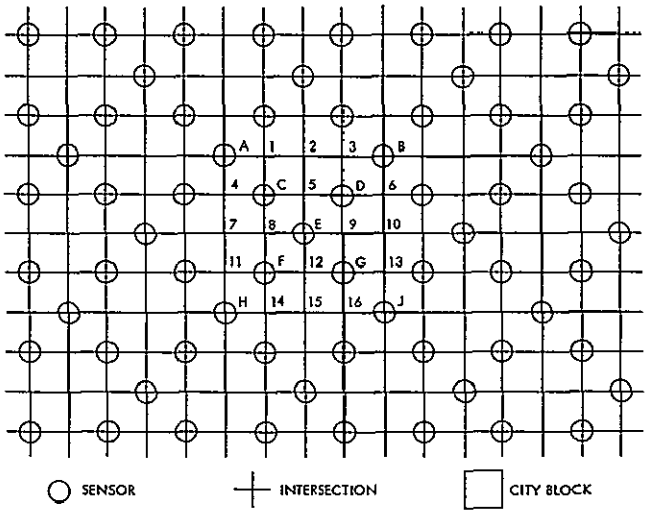


Fig. 3-5. Urban Distribution Pattern for Monitored Proximity Sensors

The number of sensors, their layout, and transition probabilities between orthogonally adjacent intersections is required a priori information. Uniformity 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 probability.

If one were to incorporate a different transition probability for each of the four possible directions, the number of states in the Markov chain model would increase fourfold. Each state would be associated 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 probabilities were accurately known. That is, 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 assumed. 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 transition 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 x 25 in Fig. 3-5) for a Markov chain model of an entire 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 α = NC and $[2N - I]\alpha - \alpha_{sq}$ were computed on an IBM 360/65. The components of α and α_{sq} rounded to 3 decimal places are:

	α = NC	α_{sq}
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
8	1.667	2.778
9	1.667	2.778
10	2.667	7.111
11	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

	1	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
16	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 Chain 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

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

Since 1.778 is a fraction of 2.778 and 7.111 (the distinct entries of α_{sq}), the means given in α are reliable estimates for the layout in Fig. 3-5.

Note that the probability of being sensed cannot be computed. The probability of being 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) + 4 (each shared by 4 subareas)/4 + 12 (each shared by 2 subareas)/2 or 16. Thus the ratio of sensed intersections to total intersections is 3/8.

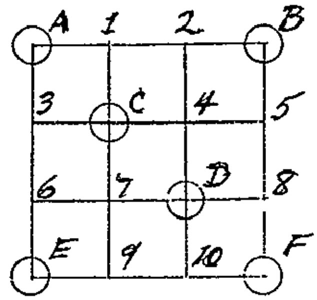


Fig. 3-8. Monitored Subarea with Sensor Density of 3/9

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 decimal 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	2	3	4	5	6	7	8	9	10
1	0	.25	0	0	0	0	.25	0	0	0
2	.25	0	0	.25	0	0	0	0	0	0
3	0	0	0	.25	0	.25	0	0	0	0
4	0	.25	0	0	.25	0	0	0	0	0
5	0	0	0	.25	0	0	0	.25	0	0
6	0	0	.25	0	0	0	.25	0	0	0
7	0	0	0	0	0	.25	0	0	.25	0
8	0	0	0	0	.25	0	.25	0	0	0
9	0	0	0	0	0	0	.25	0	0	.25
10	0	0	0	.25	0	0	0	0	.25	0

Fig. 3-9. Submatrix Q of Absorbing Chain Model for Monitored Subarea in Fig. 3-8

	A	B	C	D	E	F
1	.25	0	.25	0	0	0
2	0	.25	0	.25	0	0
3	.25	0	.25	0	0	0
4	0	0	.25	.25	0	0
5	0	.25	.25	0	0	0
6	0	0	0	.25	.25	0
7	0	0	.25	.25	0	0
8	0	0	0	.25	0	.25
9	0	0	.25	0	.25	0
10	0	0	0	.25	0	.25

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

	1	2	3	4	5	6	7	8	9	10
1	1 073	0 29	0 021	0 089	0 024	0 083	0 311	0 006	0 083	0 021
2	0 287	1 15	0 006	0 311	0 083	0 024	0 089	0 021	0 024	0 006
3	0 021	0 083	1 073	0 311	0 083	0 29	0 089	0 021	0 024	0 006
4	0 077	0 308	0 003	1 156	0 308	0 012	0 044	0 077	0 012	0 003
5	0 021	0 083	0 006	0 311	1 15	0 024	0 089	0 287	0 024	0 006
6	0 006	0 024	0 287	0 089	0 024	1 15	0 311	0 006	0 083	0 021
7	0 003	0 012	0 077	0 044	0 012	0 308	1 156	0 003	0 308	0 077
8	0 006	0 024	0 021	0 089	0 29	0 083	0 311	1 073	0 083	0 021
9	0 006	0 024	0 021	0 089	0 024	0 083	0 311	0 006	1 15	0 287
10	0 021	0 083	0 006	0 311	0 083	0 024	0 089	0 021	0 29	1 073

FIG 7 The Fundamental Matrix N Corresponding to Fig 4

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

REFERENCE

1. Kemeny, J. G., and Snell, J. L., Finite Markov Chains, D. Van Nostrand Co., Inc., Princeton, N. J., 1960

PART FOUR:

AM BROADCAST AND BURIED LOOP FEASIBILITY ANALYSES FOR AVM USE

G.R. Hansen
L.J. Zottarelli

CONTENTS

FIGURES

TABLES

G. R. Hansen

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 coordinates 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 three 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 is 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 receivers to extract the carrier frequencies and also a second set of three phase-locked 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.

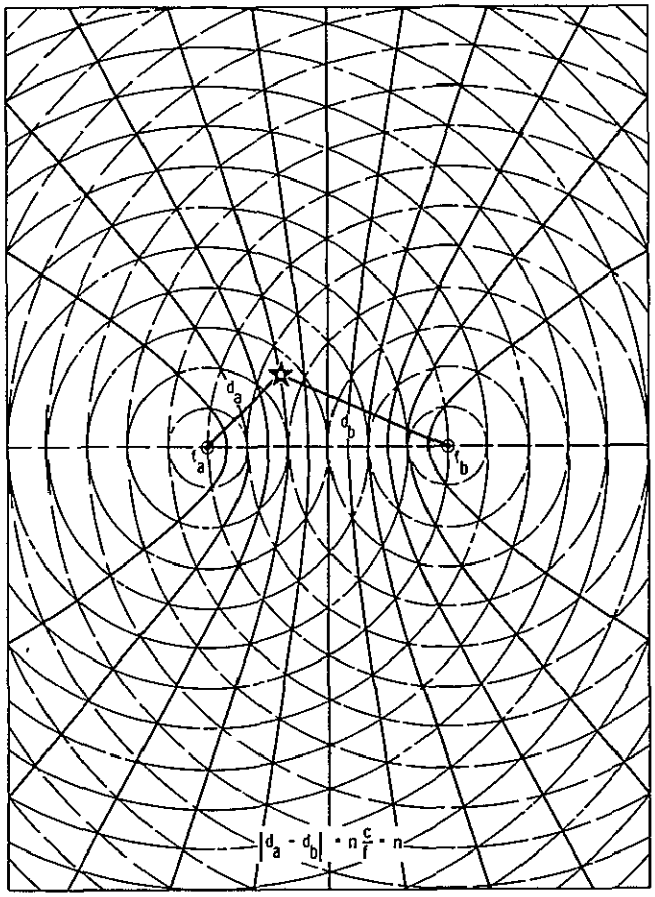


Fig. 4-1. Zero Degree Phase Difference Hyperbolic Contours Produced by Pair of Synchronized RF Signals

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.)

*U.S. Patent 3,889,264.

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 will 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 receiver 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 LOP 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 cyclically at a rate determined by the difference in frequency. This rate will be the same anywhere that the two signals can be received. 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

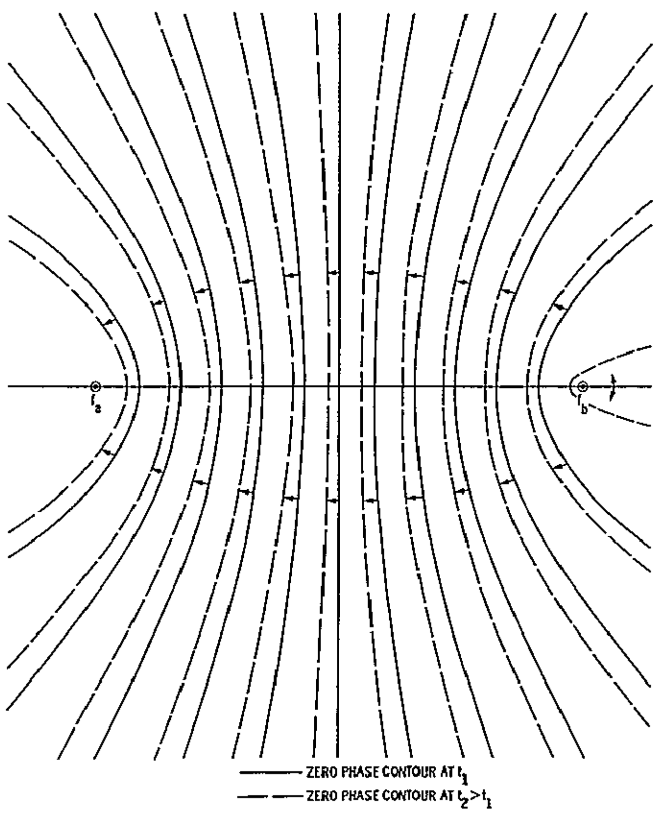


Fig. 4-2. Apparent Motion of Hyperbolas Due to Slight Difference in Two Signal Frequencies

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 receiver 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 receiver 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 principal 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 maintain 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 sites 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 Bibliography), 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 restraints requires that this common frequency be a multiple of the highest common divisor of the available AM carriers. The common frequency should therefore be a multiple of 10 kHz.

The individual AM carrier signals are received by the vehicle receivers, and these 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 received; 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

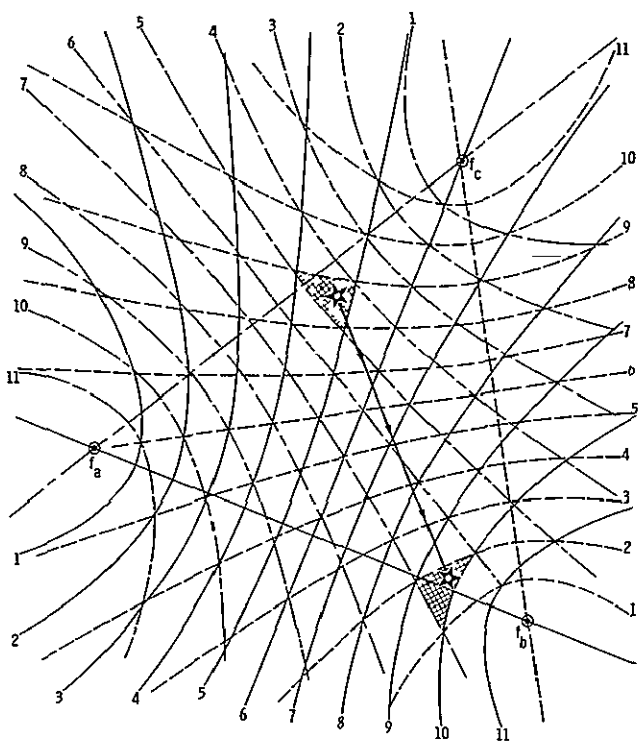


Fig. 4-3. Change in Receiver Location from Hyperbolic Area 5-9-5 to 10-2-7

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 this AVM system, the computational ability 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 fixed, then only the counts accumulated by moving receivers are necessary to determine the new positions from the old. If the grid is moving, then the difference in counts between the moving receivers 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 while 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 receivers to be installed in the vehicles is shown in Fig. 4-4.

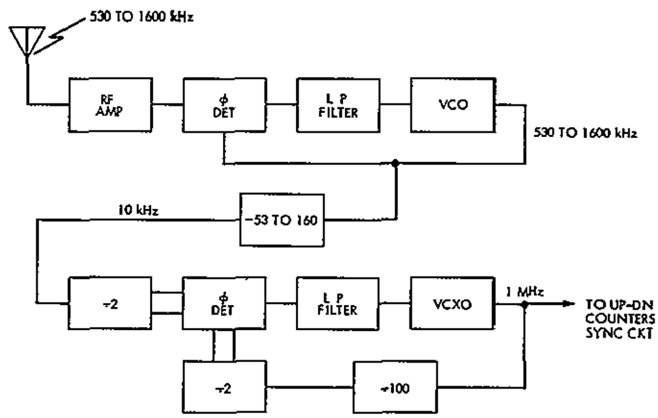


Fig. 4-4. Phase-Locked Loop AM Receiver on Vehicle for Hyperbolic AVM Technique

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 flip-flop 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 voltage-controlled 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 is 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 MHz signals, each phase-coherent with the appropriate AM carrier.

The problem then remains to determine the ID number and direction of the hyperbola that is 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 incrementing 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 simultaneous 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 is lost or split. The logic for resynchronizing to 4.192 MHz is shown in Fig. 4-5. The logic discards both incrementing and decrementing pulses which are inputs to the same up-down counter and arrive in the same synchronizing interval.

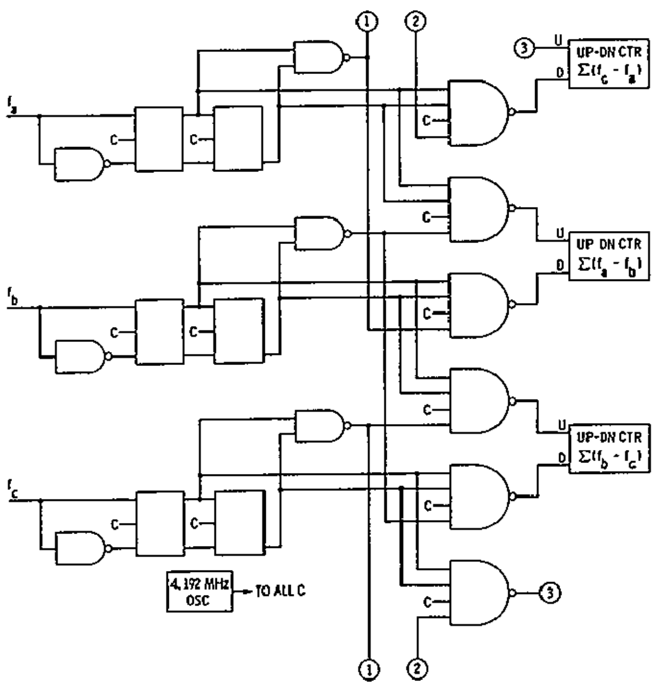


Fig. 4-5. Up-Down Counters Sync Logic for Hyperbolic AVM Technique

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 (i.e., not exactly on the assigned frequency) and part is due to vehicular motion.

D. Vehicle Location Method

If three AM 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 f_c, then the three counters in the vehicles will accumulate counts N in a time t in accordance with:

$$N_a = (f_a - f_b)t + V_{ab}\,(f)t \times F(x,y) \div C$$

$$N_b = (f_b - f_c)t + V_{bc}\,(f)t \times G(x,y) - C$$

$$N_c = (f_c - f_a)t + V_{ca}\,(f)t \times H(x,y) - C$$

$$C = 3 \times 10^9 \text{ m/sec}$$

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 in 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 N_{a1}, N_{b1}, and N_{c1}, respectively). The coordinates in X and Y and the counter states are stored. The counter states of the stationary receiver are also stored at the same instant. An explicit calculation is 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 available 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 within 20 Hz of the assigned frequency. If all the AM stations within a given 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 is 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 carriers 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) $\pm X \text{ Hz} = \pm 20 \text{ Hz } (10^6 \text{ Hz})/f \text{ Hz}$, where f is the AM 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 will be discussed later.

A secondary effect of the AM carrier being off frequency and thereby 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 polling 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 vehicles 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 identify 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 received matches the number assigned to the vehicle, a data transmission is initiated from the vehicle. The inclusion of a respond or do-not-respond 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 km/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 information was added to the basic 39 bits of location data. Assuming the higher number over a voice channel from the vehicle which could conservatively accommodate 1200 bit/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 times 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 maintained phase coherency. A stationary location 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 relatively small amount of equipment would be necessary at each AM station to maintain the carriers coherent to one another. This could be done by either 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 carriers, or transmitter switchover when power is increased or reduced. In some smaller metropolitan 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 generator called PIG (Table 4-2) were written to test the location method. A SETΔUP program (Table 4-3) was also written which stores the locations of the AM stations in the arbitrary coordinate system and determines the lengths of the baselines connecting the stations.

Table 4-1. Vehicle Location Simulator Program, LOCATE

```
      ∇LOCATE[⎕]∇
    ∇ LOCATE
[1]   XS←4↑XS,XS[1]
[2]   YS←4↑YS,YS[1]
[3]   D←3⍴0
[4]   X←Z1[1]
[5]   Y←Z1[2]
[6]  RP L←1
[7]   D←(((X-XS)*2)+(Y-YS)*2)*0 5
[8]   D←D D[1]
[9]   C←3⍴0
[10] RE A[L]←((X-XS[L])÷D[L])-((X-XS[1])÷D[1])
[11]  OC←(0 (CTR[1]-LAN[1]),(LA [3]-CTR[3]))×300
[12]  B[L]←((Y-YS[L])÷D[L])-((Y-YS[1])÷D[1])
[13]  CY[L]←(D[L]-D[1])-Q[L]+OC[ ]
[14]  →RE×⍳(3≥L←L+1)
[15]  DEN←((+/A*2)×(+/B*2))-(+/(A×B))*2
[16]  ΔX←(((+/A×CY)×(+/B*2))-((+/B×CY)×(+/A×B)))÷DEN
[17]  ΔY←(((+/A*2)×(+/B×CY))-((+/A×B)×(+/A×CY)))÷DEN
[18]  X←X-ΔX
[19]  Y←Y-ΔY
[20]  →RP×⍳(((|ΔX)>10)∨((|ΔY)>10))
[21]  OLD←X,Y
[22]  'NEW X AND Y ARE ',OLD
[23]  'ΔX AND ΔY ARE ' (X-X),(Y-Y)
    ∇
```

In order to make the simulation more realistic, three AM stations in the Los Angeles, CA, metropolitan area were chosen: KFI (640 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 Civic 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

```
      ∇PIG[⎕]∇
    ∇ OLD PIG Z2
[1]   XS←Z1←YS←DC←DD←CTR←CRT←N←Q←3⍴0
[2]   X←Z1[1]←OLD[1]
[3]   Y←Z1[2]←OLD[2]
[4]   XS←X1,X2,X3
[5]   YS←Y1,Y2,Y3
[6]   DC←(((X-XS)*2)+((Y-YS)*2))*0 5
[7]   NO←(DC[2]-DC[1]),(DC[3]-DC[2]),(DC[1]-DC[3])
[8]   NO←NO÷300
[9]   LAN←C÷300
[10]  CTR←⌊(NO+LAN+0 5)
[11]  'OLD COUNTER WAS ' CTR
[12]  X←X←Z2[1]
[13]  Y←Y←Z2[2]
[14]  DD←(((X-XS)*2)+((Y-YS)*2))*0 5
[15]  NN←(DD[2]-DD[1]),(DD[3]-DD[2]) (DD[1]-DD[3])
[16]  NN←NN÷300
[17]  CRT←⌊( NN+LAN+0 5)
[18]  'NEW COUNTER IS  ' CRT
[19]  N←CRT-CTR
[20]  'CHANGE WAS      ' N
[21]  Q←(0,(N[1]) (-N[3]))×300
    ∇
```

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

```
      ∇SETΔUP[ ]]∇
    ∇ SETΔUP
[1]   G←E←F←A←B←3⍴0
[2]   'SET X AND Y FOR EACH OF THREE AM STATIONS IN METERS '
[3]   C←⎕
[4]   X1←C[1]
[5]   X2←C[3]
[6]   X3←C[5]
[7]   Y1←C[2]
[8]   Y2←C[4]
[9]   Y3←C[6]
[10]  A←((X2+X1)÷2),((X3+X2)÷2),((X1+X3)÷2)
[11]  B←((Y2+Y1)÷2),((Y3+Y2)÷2),((Y1+Y3)÷2)
[12]  E←(X2-X1),(X3-X2),(X1-X3)
[13]  F←(Y2-Y1),(Y3-Y2),(Y1-Y3)
[14]  L←1
[15] RE G[L]←((E[L]*2)+(F[L]*2))*0 5
    ∇
```

An arbitrary origin for the coordinate system was located some 8 km (5 miles) 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 X-Y system. The origin is at 118°30'W and 33°45'N.

The location (LOCATE) program and the vehicle count generator (PIG) program were written in APL computer language. The vehicle count generator requires two input variables. These are the initial and terminal values in meters of the X-Y coordinates representing each change of position of the vehicle. The hyperbolic coordinates of each location are calculated and the integral difference 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 initial location are the inputs to the LOCATE routine which determines the new location. The new location is determined by a reiterative 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 available, 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 (1) dedicated transmitters for location purposes are not required and that (2) the phase-lock-loop counting receivers 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.

II. VEHICLE LOCATION BY MEANS OF BURIED LOOPS*

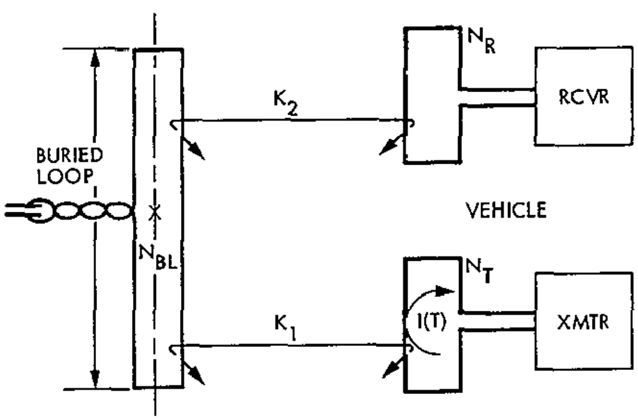
Lawrence J. Zottarelli

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

A. Relationships of Three-Loop Vehicle Location System

The approach is 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 directly proportional to the number of turns.
3. The loops are in an isotropic medium.



I(T) = XMTR CURRENT
K_1 = XMTR/BL COUPLING
K_2 = RCVR/BL COUPLING
N_R = RCVR TURNS
N_T = XMTR TURNS
N_{BL} = BURIED LOOP TURNS
R_{BL} = BL RESISTANCE

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 Φ coupling the buried loop (BL) due to the XMTR current I(T) at point P is

$$\Phi_{BL} = K_1 \cdot N_T \cdot I(T)$$

where

$I(T) = I_P \sin(wt)$, K_1 = XMTR/BL coupling, and N_T = XMTR turns.

(2) The voltage E coupled to the buried loop with width W is

$$E_{BL}(T) = N_{BL}\, d\Phi_{BL}/dt = W \cdot K_1 \cdot N_T \cdot N_{BL} \cdot I_P \cdot \cos(wt)$$

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

$$I_{BL}(T) = E_{BL}(T)/R_{BL} = \left[K_1 \cdot N_T \cdot N_{BL} \cdot W \cdot I_P \cdot \cos(wt)\right]/R_{BL}$$

(4) The flux lines coupling K_2 the RCVR due to the buried loop is

$$\Phi_{RCVR}(T) = K_2 \cdot N_{BL} \cdot I_{BL}(T)$$

substituting

$$\Phi_{RCVR}(T) = \left[-K_1 \cdot K_2 \cdot N_T \cdot (N_{BL})^2 \cdot W \cdot I_P \cdot \cos(wt)\right]/R_{BL}$$

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

$$E_{RCVR} = N_R\, d\Phi_{RCVR}/dt = \left[-K_1 \cdot K_2 \cdot N_T \cdot N_{BL} \cdot N_R \cdot (W\, I_P)^2 \cdot \sin(wt)\right]/R_{LOOP}$$

allowing now the resistance per turn (R/turn)

$$R_{loop} = (R/turn) \cdot N_{BL}$$

QED: $$E_{RCVR} = \left[-K_1 \cdot K_2 \cdot N_T \cdot N_{BL} \cdot N_R \cdot (W\, I_P)^2 \cdot \sin(wt)\right]/(R/turn)$$

*U.S. Patent 3,772,691, "Automatic Vehicle Location System."

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 E_{rcvr} is to be of the form MdI/dt then:

$$M_{equivalent} \text{ becomes} \left[K_1 \cdot K_2 \cdot N_T \cdot N_R \cdot N_{BL} \cdot (WIP)\right] / (R/turn)$$

and

I(t) becomes IP cos(wt)

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 linkage or mutual inductance of two parallel planar loops (nôt 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

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

(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 Artificial 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 size 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

```
.TYPE LOOPS SAI
  BEGIN "LOOPS"
  INTERNAL INTEGEP EXIT ,FOPER.;
  INTEGEP I,J,S,BFK,
  DEFINE RF="'15&'12";
  PEAL X,XMIN, MAX Y,YMIN,YMAX,,END.XA YA,A,B,C,D,E HA.BB.CC,DD,F,
  G,H,K,L,M,N,G,P,P,T,Q,BZ,Z,YES,NO,
  STRING ST,
  OUTSTR("DO YOU WANT NOTES (TYPE IN EITHER YES OP NO FOLLOWED BY
CAR RET)  "),

  IF INCHWL="YES"  THEN OUTSTR("
    THE PURPOSE OF THIS PPOGPAM IS TO CALCULATE THE FREE SPACE
  RELATIVE COUPLING PETWEEN TWO FLAT BUT NON COPLANAR FECTANGULAP
  LOOPS OF WIRE(THE SIDES OF WHICH ARE PAPALLEL TO THE COOFDINATE
  AXES OF PEFPANCE)   IT IS TO BE APPLIED IN AUTOMOTIVE VEHICLE
  LOCATION HENCE THE TENOP OF THE FOLLOWING INTRODUCTION.
    THE LANE WIDTH IS THE X DIMENSION THE LANF LENGTH IS
  THE Y DIMENSION,THE VERTICAL DISTANCE BETWEEN LOOPS IS THE
  Z DIMENSION   THE CENTER OF THE BUPIED LOOF IS AT COORDINATES
  0,0,0   THE WIDTH OF THE BURIED LOOP IS THE LANE WIDTH
    K IS THE ASPECT RATIO OF THE BURIED LOOP (WIDTH DIVIDED BY
  LENGTH)
    XMIN,XMAY,YMIN,YMAX DETERMINE THE SIDES AND LOCATION OF THE
  PICKUP LOOP
    ALL INFUT DIMENSIONS ARE TO BE NORMALIZED TO HALF THE LANE
  WIDTH.
    HOW MANY STEPS PEFERS TO MOVING THE PICKUP LOOP ALONG
  THE LANE LENGTH(GENERALLY AWAY FROM ABOVE THE BURIED LOOP) BY
  1/10 OF THE PICKUP LOOP LENGTH AND THEN CALCULATEING ITS
  NORMALIZED Z DIPECTION COUPLING FROM THE BURIED LOOP.
    THE FPINTOUT IS THE CALCULATED FLUX IN PELATIVE FLUX UNITS
  AND OF SUCCESSIVE STEFPINGS
    TO FIND THE ACTUAL FLUX IN VOLT SECONDS,MULTIPLY THE DATA
  BY THE FOLLOWING FACTOP:
          (I)*(LANE WIDTH/2)*(10↑(-7))
  WHEPE I IS THE BURIED LOOP CURRENT IN AMPS
  WHERE THE LANE WIDTH IS IN METERS"&RF);
  OUTSTR("HOW MANY STEPS ");
  Q←(10*(REALSCAN((ST←INCHWL),BRK))), OUTSTR(RF).
  PEGIN
  PEAL ARRAY V[1:Q],
  OUTSTR("XMIN="),XMIN←REALSCAN((ST←INCHWL),BRK); OUTSTR(FF),
  OUTSTR("XMAX="),XMAX←REALSCAN((ST←INCHWL),BRK)  OUTSTR(RF);
  OUTSTR("YMIN="),YMIN←PEALSCAN((ST←INCHWL),BRK), OUTSTR(RF);
  OUTSTR("YMAX="),YMAX←PEALSCAN((ST←INCHWL),BRK), OUTSTR(RF);
  X←XMIN;XA←(YMAX-XMIN)/10,
```

Table 4-4. (Continued)

```
Y+YMIN YA+(YMAX-YMIN)/10;
YEND+YMIN+YA+Q
T+0,Z+1,B+0,
OUTSTR("Z="),Z+REALSCAN((ST+INCHWL),BRK); OUTSTR(RF);
E+Z↑2,J+1 I+1
OUTSTR("Y="),Y+REALSCAN((ST+INCHWL),BRK), OUTSTR(RF);
EXIT +0,FORER +0
BEGIN
PROCEDURE BIZ,
BEGIN
  A+(X+1),B+(Y-1),
  C+(Y+K),D+(Y-K),
  AA+(X+1)↑2,CC+(Y+K)↑2;
  BB+(X-1)↑2,DD+(Y-K)↑2;
  F+(E+DD+AA)↑( 5),G+(E+CC+AA)↑( 5);
  H+(E+DD+BB)↑( 5),N+(E+CC+BB)↑( 5),
  P+(A/(E+AA))+(-D/F+C/G),
  R+-(B/(E+BB))+(-D/H+C/N);
  L+(C/(E+CC))+(-B/N+A/G)
  M+-(D/(E+DD))+(-B/H+A/F);
  BZ+(P+R+L+M)+XA+YA, .
END,

PROCEDURE FLUXCUP,
BEGIN
  SETFORMAT(13,3),
  WHILE Y GEQ YMIN AND Y LEQ (YEND-( 9999)+(YA)) DO
  BEGIN
    WHILE X GEQ XMIN AND X LEQ ( XMAX-( 999)+(XA)) DO
    BEGIN
      BIZ; T+T+BZ,X+Y+XA
    END,
    V[S]+T,X+XMIN,Y+Y+YA,S+S+1,T+0
  END,
  WHILE J LEQ (S-10) DO
  BEGIN
    WHILE (J+10)>I DO
    BEGIN
      O+O+V[I],I+I+1
    END,
    OUTSTR(CVE(O)),
    O+0,J+J+1, IF (I MOD 5) = 0 THEN OUTSTR(RF),I+J
  END,
END,
FLUXCUP,
END,END;
END "LOOPS"
```

```
RUN LOOPS .AV

DO YOU WANT NOTES (TYPE IN EITHER YES OR NO FOLLOWED B, CAR RET)  YES

  THE PURPOSE OF THIS PROGRAM IS TO CALCULATE THE FREE SPACE
RELATIVE COUPLING BETWEEN TWO FLAT BUT NON COPLANAR RECTANGULAR
LOOPS OF WIRE(THE SIDES OF WHICH ARE PARALLEL TO THE COORDINATE
AXES OF REFERANCE)   IT IS TO BE APPLIED IN AUTOMOTIVE VEHICLE
LOCATION HENCE THE TENOR OF THE FOLLOWING INTRODUCTION.
  THE LANE WIDTH IS THE X DIMENSION THE LANE LENGTH IS
THE Y DIMENSION THE VERTICAL DISTANCE BETWEEN LOOPS IS THE
Z DIMENSION.  THE CENTER OF THE BURIED LOOP IS AT COORDINATES
0,0,0   THE WIDTH OF THE BURIED LOOP IS THE LANE WIDTH
  K IS THE ASPECT RATIO OF THE BURIED LOOP (WIDTH DIVIDED BY
LENGTH)
  XMIN,XMAX,YMIN,YMAX DETERMINE THE SIDES AND LOCATION OF THE
PICKUP LOOP
  ALL INPUT DIMENSIONS ARE TO BE NORMALIZED TO HALF THE LANE
WIDTH.
  HOW MANY STEPS REFERS TO MOVING THE PICKUP LOOP ALONG
THE LANE LENGTH(GENERALLY AWAY FROM ABOVE THE BURIED LOOP) BY
1/10 OF THE PICKUP LOOP LENGTH AND THEN CALCULATING ITS
NORMALIZED Z DIRECTION COUPLING FROM THE BURIED LOOP
  THE PRINTOUT IS THE CALCULATED FLUX IN RELATIVE FLUX UNITS
AND OF SUCCESSIVE STEPPINGS
  TO FIND THE ACTUAL FLUX IN VOLT SECONDS MULTIPLY THE DATA
BY THE FOLLOWING FACTOR
        (I)*((((LANE WIDTH)/2)↑2)*(10↑(-7)))
WHERE I IS THE BURIED LOOP CURRENT IN AMPS
WHERE THE LANE WIDTH IS IN METERS
HOW MANY STEPS 100

XMIN=-1

XMAX=1 000

YMIN=-0001 00

YMAX=1

Z=0

K=1

     .34392       .10299       10299       10299      .10299
      10299        10299       10299       10299       10299
     .10299      - 59091     - 30191     - 19391     - 13591
    -.10091      -.770       -.607       - 489       -.401
    - 334        - 281       - 239       - 205       - 178
    - 155        - 136       -.120       -.107       - 9569-1
    - 8519-1     - 7659-1    - 6919-1    - 6269-1    - 5699-1
    - 5199-1     - 4759-1    - 4359-1    - 4009-1    - 3699-1
    -.3419-1     - 3159-1    - 2929-1    - 2729-1    - 2539-1
    - 2369-1     - 2209-1    - 2069-1    - 1939-1    - 1819-1
    -.1709-1     - 1609-1    - 1519-1    - 1429-1    - 1349-1
    - 1279-1     - 1209-1    - 1149-1    - 1059-1    - 1029-1
    - 9709-2     -.9229-2    - 8779-2    - 8359-2    - 7969-2
    - 7599-2     -.7249-2    - 6929-2    -.6619-2    -.6329-2
    - 6059-2     -.5799-2    - 5559-2    - 5329-2    -.5119-2
    - 4909-2     -.4719-2    -.4529-2    - 4359-2    -.4189-2
    - 4039-2     - 3889-2    - 3749-2    - 3609-2    - 3479-2
    -.3359-2     - 3239-2    - 3129-2    -.3019-2    - 2919-2
    - 2829-2     - 2729-2    - 2639-2    - 2559-2    - 2479-2
    - 2399-2     - 2329-2    - 2249-2    -.2179-2    - 2119-2
    -.2059-2 END OF SAIL EXECUTION
```

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

```
TYPE CARCUP SAI
BEGIN "CARCUP"
INTERNAL INTEGER EXIT ,FORER.,
INTEGER I,J,Q,Z,S,BRK;
DEFINE RF="'15&'12",
REAL X,XTMIN,XTMAX,Y,YTMIN,YTMAX,YEND,XA,YA,A,B,C,D,E,AA,BB,CC,D
D,F,
G,H,K,L,M,N,O,P,R,T,BZ,YES,NO,XRMIN,XRMAX,YRMIN,YRMAX,ZT,ZP,
REAL XMIN,YMIN,XMAX,
STRING ST;
OUTSTR("DO YOU WANT NOTES (TYPE IN EITHER YES OR NO THEN CAR RET
) "),
IF INCHWL ="YES" THEN OUTSTR("TO FIND THE ACTUAL OUTPUT VOLTS,.M
ULTIPLY THE DATA BY THE FOLLOWING
    -(NT*NBL*NR*(((10↑(-7))*(LANE WIDTH/2)↑2))↑2)*(W↑2)*(IP↑2)*SI
N(WT))/R
     WHERE
        NT = NUMBER OF TURNS ON THE TRANSMITTER LOOP
        NBL = NUMBER OF TURNS ON THE BURIED LOOP
        NR = NUMBER OF TURNS ON THE RECIEVER LOOP
        LANE WIDTH IS IN METERS
        W = 2*PI*F
        F = TRANSMITTER FREQUENCY (HERTZ)
        IP = THE PEAK TRANSMITTER CURRENT
        SIN(WT) = YOU KNOW WHAT
        R = THE PER TURN RESISTANCE OF THE BURIED LOOP
        / = DEVIDE, * = MULTIPLY, ↑ = TO THE POWER OF
        "&RF),
OUTSTR("HOW MANY STEPS "),
Q+(10*(REALSCAN((ST+INCHWL),BRK))), OUTSTR(RF),
BEGIN
REAL ARRAY V[1 Q],REAL ARRAY W[1 (Q-9)]

OUTSTR("XTMIN=") XTMIN+REALSCAN((ST+INCHWL),BRK), OUTSTR("   "),
OUTSTR("XTMAX="),XTMAX+REALSCAN((ST+INCHWL),BRK), OUTSTR("   ")
OUTSTR("YTMIN=") YTMIN+REALSCAN((ST+INCHWL),BRK), OUTSTR("   "),
OUTSTR("YTMAX=") YTMAX+REALSCAN((ST+INCHWL),BRK), OUTSTR("   "),
OUTSTR("ZT="),ZT+REALSCAN((ST+INCHWL),BRK), OUTSTR(RF),
OUTSTR("XRMIN="),XRMIN+REALSCAN((ST+INCHWL),BRK), OUTSTR("   "),
OUTSTR("XRMAX="),XRMAX+REALSCAN((ST+INCHWL),BRK), OUTSTR("   ");
OUTSTR("YRMIN=");YRMIN+REALSCAN((ST+INCHWL),BRK), OUTSTR("   ")
OUTSTR("YRMAX="),YRMAX+REALSCAN((ST+INCHWL),BRK), OUTSTR("   "),
OUTSTR("ZR=") ZR+REALSCAN((ST+INCHWL) BRK), OUTSTR(RF)
OUTSTR("K=") K+REALSCAN((ST+INCHWL),BRK), OUTSTR(RF),
EXIT.+0 FORER +0,
BEGIN
PROCEDURE BIZ,
BEGIN
  A+(X+1),B+ Y-1),
  C+(Y+K),D+(Y-K),
  AA+(X+1)↑2,CC+(Y+K)↑2,
  BB+(X-1)↑2;DD+(Y-K)↑2,
  F+(E+DD+AA)↑( 5),G+(E+CC+AA)↑( 5),
  H+(E+DD+BB)↑(.5),N+(E+CC+BB)↑( 5);
  P+(A/(E+AA))+(-D/F+C/G)
  R+-(B/(E+BB))+(-D/H+C/N),
  L+(C/(E+CC))+(-B N+A/G),
  M+-(D/(E+DD))+(-B/H+A/F),
  BZ+(P+R+L+M)+ A+YA;
END,

PROCEDURE FLUXCUP,
BEGIN
  WHILE Y GEQ YMIN AND Y LEQ (YEND-( 9999)+(YA)) DO
  BEGIN
    WHILE X GEQ XMIN AND X LEQ ( XMAX-(.999)+(XA)) DO
    BEGIN
      BIZ; T+T+BZ,X+X+XA
    END,
    V[S]+T,X+XMIN,Y+Y+YA S+S+1;T+0
  END,
  WHILE J LEQ (S-10) DO
  BEGIN
    WHILE (J+10)>I DO
    BEGIN
      O+O+V[I],I+I+1
    END,
  W[I-10]+W[I-10]+O,
    O+0,J+J+1,I+J,
  END
END,
Z+1,WHILE Z LEQ (Q-9) DO
BEGIN
    W[Z]+1,
    Z+Z+1
END,
T+0,S+1,O+0
X+XTMIN,XA+(XTMAX-XTMIN)/10,Y+YTMIN YA+(YTMAX-YTMIN)/10,
YEND+YTMIN+YA+Q,YMIN+YTMIN,XMIN+XTMIN,XMAX+XTMAX,

E+ZT↑2,J+1,I+1;
FLUXCUP,
T+0,S+1,O+0;
X+XRMIN,XA+(XRMAX-XRMIN)/10,Y+YRMIN,YEND+YRMIN+YA+Q,
YA+(YRMAX-YRMIN)/10,YMIN+YRMIN XMIN+XRMIN XMAX+XRMAX,
E+ZR↑2 J+1,I+1,
FLUXCUP,
SETFORMAT(13,3),I+1,
WHILE I LEQ (Q-9) DO
   BEGIN
     OUTSTR(CVE(W[I]))
       IF (I MOD 5)=0 THEN OUTSTR(RF),
        I+I+1
    END,
END END
END "CARCUP"
```

Table 4-5. (Continued)

```
.RUN CARCUP.SAV

DO YOU WANT NOTES (TYPE IN EITHER YES OR NO THEN CAR RET) YES
TO FIND THE ACTUAL OUTPUT VOLTS, MULTIPLY THE DATA BY THE FOLLOWING
   -(NT*NBL*NR*(((10↑(-7))*(LANE WIDTH/2)↑2,)↑2)*(W↑2)*(IP↑2)*SIN(WT)) R
      WHERE
         NT = NUMBER OF TURNS ON THE TRANSMITTER LOOP
         NBL = NUMBER OF TURNS ON THE BURIED LOOP
         NR = NUMBER OF TURNS ON THE RECIEVER LOOP
         LANE WIDTH IS IN METERS
         W = 2*PI*F
         F = TRANSMITTER FREQUENCY (HERTZ)
         IP = THE PEAK TRANSMITTER CURRENT
         SIN(WT) = YOU KNOW WHAT
         R = THE PER TURN RESISTANCE OF THE BURIED LOOP
         / = DEVIDE, * = MULTIPLY, ↑ = TO THE POWER OF

HOW MANY STEPS 30

XTMIN= 45
  XTMAX= 55
  YTMIN=- 05
  YTMAX= 05
  ZT=.1

XRMIN=-.55
  XRMAX=-.45
  YRMIN=- 05
  YRMAX= 05
  ZR=.1

K= 4

      119D-1      119D-1      120D-1      .120D-1      120D-1
      121D-1      122D-1      123D-1      .125D-1      126D-1
      128D-1      130D-1      132D-1      .134D-1      137D-1
     .140D-1      143D-1      147D-1      .150D-1     .154D-1
     .159D-1     .163D-1      168D-1      .172D-1     .177D-1
      181D-1      185D-1      188D-1      .191D-1     .191D-1
     .189D-1 END OF SAIL EXECUTION
```

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 prints 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-direction (along the roadway lane) by 1/10 of the XMTR length. The results are in units of relative mutual inductance and to get real answers, answer "yes" when the program asks if you want more detailed 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.

$$\Delta X = (XMAX-XMIN)/10$$

$$\Delta Y = (YMAX-YMIN)/10$$

The swept-out area is divided into portions having dimensions ΔY 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 subroutine procedures used to calculate the mutual inductances, 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 ≥ 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 x 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 ≥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 height the coupling varies with later position, being highest near 0.8ℓ from center to end of the buried loop. The variation between these limits is about 10%.

If a sensor loop is placed lower than the optimum height, it results in overcoupling and relatively 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 differing shapes will function and may permit three-loop systems whereby the smallest moving coil may be made the optimal for signal to "noise" ratio.

3. Expected real-life signal levels. The following configurations and conditions are assumed: (1) Roadway with lane width 2ℓ = 3 meters, (2) buried loops with aspect ratio K = 0.1 and separated by $4 \times k \times \ell$, (3) pickup loops (XMTR and RCVR) having sides $P = 0.1\ell$, height $Z = 0.1\ell$, and separated by ℓ. (4) All loops have 10 turns each of #27 wire and resistivity of 1.36 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 transmitter and receiver produces a voltage at the receiver 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.

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