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EQUIPMENT SYSTEMS IMPROVEMENT PROGRAM

A STUDY OF INTEGRATED LOCATION SYSTEMS

Law Enforcement Development Group

September 1976

Prepared for

National Institute of Law Enforcement and Criminal Justice
LAW ENFORCEMENT ASSISTANCE ADMINISTRATION
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The Aerospace Corporation

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EQUIPMENT SYSTEMS IMPROVEMENT PROGRAM
SYSTEM ACCEPTANCE ACTION PLAN

Approved

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ABSTRACT

This report discusses the use of the Citizen Alarm System in an integrated mode, combining the personal alarm function with a vehicle location function. The cost/effectiveness aspects of dual usage are investigated for alternative deployments in terms of expected cost per criminal apprehension attributable to the system.

In addition, two operational problems are investigated; mutual interference of radio signals from two or more vehicle-borne transmitters to a receiver and data rate saturation of the communication links.

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I. EXECUTIVE SUMMARY

The application of the citizen alarm system for vehicle location is analyzed in terms of cost/effectiveness and operational feasibility.

The purpose of the system is to provide a method for the citizen to immediately summon the police in the event of a criminal attack. The citizen carries a small, compact actuator which transmits an alarm signal by radio upon command to one of a number of fixed receiver-relays. These receiver-relays then retransmit the alarm signal along with location information to a control center which dispatches a police officer to the scene. The object of the system is the immediate apprehension of the suspect and protection of the victim.

An automatic vehicle monitoring system provides timely location data along with status information of selected groups of vehicles for such applications as police patrol vehicle dispatching, bus scheduling, taxi dispatching, and truck cargo security. Since both vehicle monitoring and citizen alarm systems require locational data to be transmitted to a control center, the possibility of using a single system for both functions has been considered.

First, the alternative deployments of the citizen alarm system throughout a city are investigated. Chicago is selected for the analysis since detailed crime and police data are available by police district for the city. The measure of effectiveness applied is cost per apprehension. The expected number of apprehensions attributable to the system is a function of the violent crime rate, number of citizens covered, police response time, and crime duration statistics. The cost of deploying the system in an area is a function of the number of persons in the system and the number of receivers in the area.

Computing the cost per apprehension by police district results in a significant difference between high crime, high population density districts and low crime, low population density districts. Under the assumptions of the study, approximately 86% of the expected apprehensions can be accomplished in 9 of the city's 20 residential districts at about 33% of the cost of covering the whole city (see Figure VI-2). The cost per apprehension is estimated to be $1,250 for deployment only within the 9 highest crime districts and $3,320 for deployment throughout the whole city.

If vehicles are to share the citizen alarm system for vehicle location, it must be deployed throughout the city. It is estimated that approximately 10,000 vehicles might utilize a vehicle location system in Chicago. The contribution of these vehicle users to the cost of the citizen alarm system is assumed to be such that their total expenditures do not exceed that of the least costly alternative system. The latter has been established, for large urban areas, to be a radio frequency direct proximity system (Figure V-2). Using the costs for that system to develop estimates of the vehicle users' contribution to the citizen-alarm system, it is concluded that even with as many as 10,000 vehicles sharing the system with the citizens, deployment over the whole city is not as cost effective in terms of cost per apprehension as deployment in only the high crime districts. Specifically, as given in Table VI-5, the cost per apprehension for the shared system is $2,930, only 12% less than the full deployment unshared system and more than double the value for the high crime rate area deployment.

Sensitivities of the results to receiver-relay cost, actuator cost, proportion of population covered, and number of vehicles sharing the system were investigated. As shown in Figure VI-3, the advantage of the 9-district deployment areas over the 20-district shared deployment remains over the range of receiver-relay cost factors from one-half to three (a cost factor is a multiplier applied to the base primary and secondary receiver-relay costs). The conclusions are not sensitive to changes in actuator cost (Figure VI-4) in the range from 0 to $50 annually per actuator (base cost is $27). Similarly, the percentage of eligible population who subscribe to the system does not affect the comparison between the 9-district and 20-district shared deployments (see Figure VI-5). Cost per apprehension for the 20-district shared case decreases linearly as the number of vehicles sharing the system is increased, as shown in Figure VI-6. Since the cost per apprehension for the 9-district deployment is independent of the number of vehicles, at some point the shared case will become more advantageous than the 9-district case. However, over a range from zero to 30,000 vehicles - three times the base case - the 9-district deployment is clearly more cost-effective.

Chicago was chosen for the analysis because of the availability of detailed crime and law enforcement statistics. However, the characteristics that yield great differences in expected cost per apprehension between city districts exist in most large cities in this country. Therefore, the conclusions of this analysis are generally valid for large U.S. urban centers.

Two operational aspects of the use of the citizen alarm system for vehicle location were investigated. First, if there are a number of vehicles within transmitting range of a receiver-relay, there may be contention, or mutual interference. The contention probability is a function of the vehicle density, transmission range, transmission-duty cycle, and receiver-relay spacing. The results, shown in Figures VII-4 and 5, indicate that for a reasonable range of values of these parameters there is a significant probability of contention. For example, with a 1% transmission-duty cycle,200 vehicles per square mile (less than two per block), and a transmission range of 200 feet, the contention probability is 2%, which corresponds to the Department of Transportation Automatic Vehicle Monitoring System design goal for vehicle communications coverage. Since contention is only one of the factors in the communications coverage problem, 2% represents a significant level for contention.

Secondly, the data rate generated by the vehicles is considered relative to the currently designed citizen alarm system capacity of 300 bits per second from each receiver-relay. Given a vehicle density value, the allowable transmission range for this data rate (from Figure VII-7) results in a contention probability greater than 10% (from Figure VII-4). Therefore, it appears that contention represents a more serious problem than does data-rate saturation.

II. INTRODUCTION

Over the past several years the Law Enforcement Assistance Administration of the U. S. Department of Justice has been involved in the analysis and development of a personal alarm system to be used by citizens to signal police in case of criminal attack. During this period, they have also been involved in the development of a cargo security system utilizing automatic vehicle location.

The citizens alarm system is designed to relay an alarm to the appropriate personnel and to indicate the victim's location within a specified accuracy so that the police can respond in time to apprehend the suspect. The system involves three principle components: a portable, compact signalling device (a radio transmitter), fixed receiver-relay units, and a central control station.

Automatic vehicle monitoring systems are designed to provide timely location information on certain vehicles as they travel city streets. There are many techniques for estimating vehicle location, some of which have been implemented for police patrol and bus scheduling applications. All these methods involve three basic functions: generation of location data, transmission of the data to a central control station, and computation and display. These functions are essentially the same as in the citizen alarm system, with the exception of the alarm signal (although some vehicle location applications may include an alarm function). Therefore, the development of an integrated location system useful for both the citizen alarm and the vehicle location function has been hypothesized. It is the purpose of this report to document the results of a survey and assessment of the feasibility and cost of an integrated location system.

All of the vehicle location systems developed thus far involve relatively costly, bulky, and heavy equipment to be carried in the vehicle. For this reason it is clearly not feasible to adapt any of these systems to a personal alarm application, which requires devices to be carried on the person. At present, it appears that the only implementable technique that would allow one to comfortably carry an alarm signalling device is an inverse proximity system such as the citizen alarm system. (In an inverse proximity system, the object to be located transmits signals to fixed receivers of known locations which retransmit the signals to a control center. Conversely, in a direct proximity system, signposts transmit coordinates to the object, which then retransmits location with an identification code to the control center.) It is quite possible, however, for the citizen alarm system primary receiver-relays to be used for vehicle location, either in a direct or an indirect proximity mode. The vehicle could transmit its identification to the citizen alarm system primary relays, just as the citizen transmits his identity when calling for assistance. Alternatively, the citizen alarm system relays could incorporate low power transmitters to provide the vehicle location data, which is retransmitted by the vehicle to its dispatch/control center. It is obvious, however, that the direct proximity mode provides little more integration of the two systems than that of sharing the housing and installation for the signpost and primary relay components. The total costs for integrating the location systems would be substantially greater if direct proximity is retained for vehicle location. Therefore, for this analysis it will be assumed that an integrated location system will be of the inverse proximity type. Further, since the citizen alarm system represents an inverse proximity system currently under development, the equipment configuration is defined in sufficient detail to allow credible cost estimates and deployment scenarios. For this analysis, then, the citizen alarm system will be used as the basis for the integrated location system.

The primary purpose of utilizing the citizen alarm system for vehicle location is cost savings, since two separate location systems -- the citizen alarm system and the vehicle location system -- can be replaced by the citizen alarm system alone. The overall savings then depend upon the cost required to enhance the citizen alarm system to accommodate vehicles and the amount the vehicle users save by not building a separate system. The assessment of the cost effectiveness of integrating the location systems, including the effects of alternative deployments, constitutes a major part of this report. In addition, an analysis is made of the operational requirements associated with the use of the citizen alarm system communications network by vehicle fleets. The use of the system by vehicles will result in much higher data rates than that for which it is designed. Thus, the potential problem of contention (simultaneous transmission by two or more vehicles) and the impact of higher data rates on receiver-relay design must be considered.

This report is divided into seven chapters. Chapter III describes the citizen alarm system as currently designed, while Chapter IV contains descriptions of alternative automatic vehicle location techniques. Data on unit costs for the systems considered are presented in Chapter V. Life cycle cost estimates are then developed. The cost/effectiveness analysis for shared and unshared systems is summarized in Chapter VI. Chapter VII discusses some of the operational aspects of location system integration.

III. CITIZEN ALARM SYSTEM

The purpose of the citizen alarm system (CAS) is to provide a method by which persons threatened with a crime of violence such as rape, robbery, or assault can summon police before the onset or at the beginning of the crime.[1] Ideally, the police will arrive in time to apprehend the suspect and prevent serious injury to the victim.

The system as currently envisioned consists of personal actuators which transmit radio frequency signals to a primary receiver located within a few hundred feet. The primary receiver retransmits the signal, along with its location code, to a secondary receiver by means of local power lines. The secondary receiver then transmits the data via leased dedicated telephone lines to a central control station -- generally the police dispatch center -- which dispatches a police patrol car to the location.

The system is designed to be used indoors or outdoors. However, since this analysis investigates the concurrent use of the system for vehicle location, only the outdoor configuration will be considered. The density of primary receivers dictates the location accuracy since the location uncertainty is largely dependent on the distance between detected signals.

The actuator is a compact battery-powered device using large-scale integration (LSI) technology. It is designed to be worn on the wrist or as a pendant. The coded signal is transmitted on a 452 MHz carrier frequency, with a tenth of a milliwatt output power. A design goal of 50% probability of detection at 500 feet has been established. The signal consists of 32 bits transmitted at a rate of 500 bits per second. The alarm transmissions of 15 repetitions of the coded signal occur after a two-second delay and last one second. After a 30-second interval, the transmission is repeated.

The primary receivers continuously monitor for the presence of alarm signals. When a signal is detected, the user identification data consisting of 256 bits (8 words) are stored in the primary receiver. Each primary receiver is polled in time sequence by the control center and when an alarm signal is present, it is transmitted to the control center via the secondary receiver.

To indicate the presence or absence of an alarm signal to the receiver, a two-bit code is used. Communication between the primary and secondary receivers is over 110 volt, 60 cycle commercial power lines, using a carrier frequency of 206 KHz. The carrier frequency in the reverse direction is 302 KHz. A maximum of 128 primary receivers can be interfaced with a single secondary receiver. However, in practice the ratio is much less; in fact, for street deployment, it is assumed to be ten to one.

The control center receives the data, checks for errors, determines the location of the primary receiver, decodes the user identification, and displays the resulting data in a usable form. A minicomputer is used to store the pertinent data, translate the location and identification codes, and perform the polling operation. The polling is performed independently on each dedicated line to a secondary receiver using a single timing pulse at a rate of 75 bits per second. When a receiver-relay is polled, it transmits a four-bit status word consisting of a start bit, two status bits, and a stop bit at a rate of 300 bits per second.

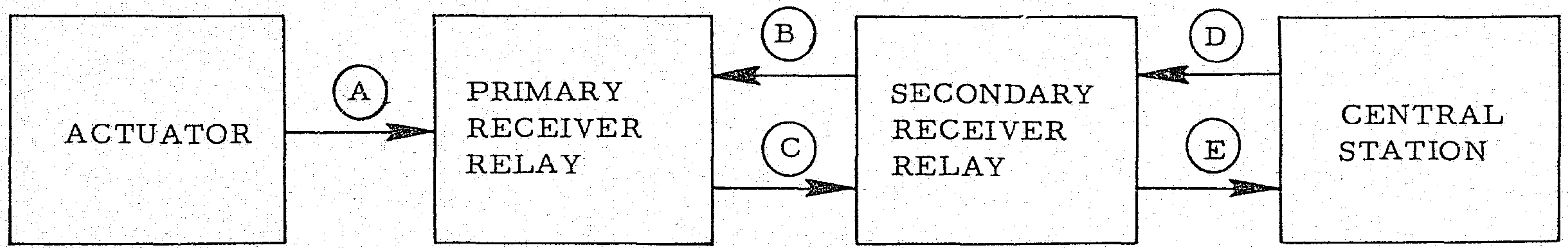
If an alarm signal is detected during the polling, the computer stops at the appropriate time slot in the next polling cycle and extracts the data from the receiver. To minimize the probability of false alarm, two out of three successive polling cycles must result in an alarm before the system acts upon it.

Figure III-1 depicts the information flow for the system. The telephone line carrier frequency is given as 1200 Hz and 2200 Hz since the modem is designed to operate in a duplex mode allowing either frequency in either direction.

Use of this system by vehicles would require a vehicle-borne device that continuously transmits the vehicle identification code. The primary and secondary receiver-relays would perform the same function as in the citizen alarm system. Polling could be performed in a similar manner by a central computer. The control center would route the vehicle data to each separate user where it would be analyzed and displayed.

Figure III-1: CITIZEN ALARM SYSTEM

Information Flow Diagram



	A	B	C	D	E
Transmission Media	UHF	Power Line	Power Line	Telephone Line	Telephone Line
Carrier Frequency	452 MHz	302 KHz	206 KHz	1200 Hz 2200 Hz	1200 Hz 2200 Hz
Data Rate	500 BAUD	75 BAUD	300 BAUD	75 BAUD	300 BAUD
Number of Bits	32 (user code)	1 (timing pulse)	4 (receiver status)	1 (timing pulse)	4 (receiver status)
Modulation	Biphase Differentially Encoded	Frequency (1 KHz)	Frequency (1 KHz)	FSK	FSK

IV. AUTOMATIC VEHICLE MONITORING SYSTEMS

A. APPLICATIONS

The automatic vehicle monitoring systems discussed in this report are designed to provide timely location data on specific sets of vehicles in an urban environment. Possible users include police patrol vehicles, buses, taxis, and commercial trucks.

1. Police

Location data can be of use to police in reducing response time for patrol vehicles. Generally, patrol vehicles are assigned sectors to patrol. When an incident occurs, the patrol vehicle for that sector is assigned if it is available. If not, a vehicle from another sector, preferably an adjacent one, is assigned. This procedure results in certain inefficiencies since the patrol vehicle assigned to a sector may be further from an incident in that sector than a patrol car in an adjacent sector. If the vehicles' locations are known to a finer degree of accuracy than by sector, the closest available vehicle can be assigned to an incident, thereby reducing response time. As has been shown[2], response time significantly affects the probability of apprehension of the suspect.

In addition, vehicle location in conjunction with a silent alarm could be useful in enhancing officer safety. An endangered patrolman, either within or outside his patrol vehicle, could covertly signal the dispatch center which could then assign an assisting officer to the appropriate location. Of course, if the signalling officer is outside his vehicle, some additional search time may be required but at least the search area would be diminished because the location of the officer's vehicle is known.

Automatic vehicle monitoring may also be useful for improving patrol supervision as it provides management with information of the location and status of each patrol vehicle at all times.

2. Buses

Urban bus companies can use location systems in a variety of ways to improve operations. These include scheduling, security, reduction of the reserve fleet and supervisory personnel, and the automatic collection of operational data.

As any urban bus rider can attest, buses on a given route tend to bunch up, thereby leaving large gaps in the arrival times at a bus stop. This problem could be alleviated if the central dispatcher knew the location of the buses as they travel their routes. He could then transmit commands to the bus drivers to adjust their schedules to achieve the desired headway gaps. For example, a bus that is behind schedule may be instructed to skip stops or a lightly loaded bus may be directed to pass a more heavily loaded bus that is behind schedule. Alternatively, a reserve bus may be sent in to fill a gap. These procedures would result in a better service and possibly increased ridership.

Every bus company maintains a reserve fleet for use in case of breakdown or delays in the regular fleet. By instantaneously reporting such occurrences, an automatic vehicle monitoring system could eliminate much of the total duration of buses out of service, thereby allowing a reduction in the reserve fleet.

An automatic vehicle monitoring system could be useful in improving the security of the bus driver and passengers by use of a silent alarm activated by the driver. The alarm signal would be transmitted to the bus dispatcher who would note the location and notify police.

Automatic vehicle monitoring could also be used to collect data on bus operations and maintenance. Such data might include records of breakdown, fuel consumption, tire mileage, etc., which can be used for preventive maintenance purposes. Many bus companies now record this type of information manually. In addition, data could be collected on travel times and number of passengers for various routes which would be useful in evaluating existing schedules.

3. Taxis

Most of the taxis in large urban areas are radio-dispatched, but there are many problems with the dispatching process. It is generally acknowledged that drivers are often reluctant to inform the dispatcher of their locations, preferring to cruise the streets rather than accept radio-dispatched assignments. The procedure that the dispatcher goes through in determining the closest available taxi to a customer is often time-consuming and inefficient in terms of use of the radio spectrum. Much of the time it does not result in assigning the closest available taxi. Automatic vehicle monitoring could alleviate these problems since the location and status of each taxi would be known to the dispatcher.

The practice of taxi drivers not using their meters for certain fares and not reporting the income to the taxi company is thought to be quite prevalent in some cities. This problem could be alleviated by use of automatic vehicle monitoring with location capability in conjunction with devices that detect the presence of passengers.

Further, automatic vehicle monitoring could enhance driver and passenger security in the same manner as described for buses; that is, a silent alarm with a location system.

4. Commercial Trucks

The fourth application of interest is cargo security for commercial trucks in an urban environment[3]. Cargo losses for such vehicles are quite high; in fact, trucking industry officials estimate their direct cargo losses from theft to be on the order of $2 billion each year. A cargo security system utilizing vehicle location and vehicle status indication is intended to reduce loss from hijacking or from theft of a portion of the cargo. Location data can also provide information useful in intercepting a hijacked vehicle. Further, location can be used, along with status data on the cargo compartment, to determine if unloading occurs at an unauthorized location.

B. SYSTEM REQUIREMENTS

An automatic vehicle monitoring system to be used for vehicle applications such as those discussed above must have the following capabilities. It must be able to cover a complete city, which implies a maximum of 480 square miles (Los Angeles). It must be able to locate vehicles travelling random routes and must be effective in high rise areas and regions of significant electromagnetic interference such as railyards, industrial plants, steel bridges, etc. Finally, it must attain a level of accuracy commensurate with the most stringent requirements of the users.

The accuracy requirements vary among users. Some police departments require a 95% probability of attaining an accuracy of 50 feet, primarily for reasons of officer security. Others require no more than a quarter of a mile[4]. For the cargo security application discussed in Reference 3, one city block is assumed. The U. S. Department of Transportation in a recent RFP for development and testing of automatic vehicle monitoring systems for urban buses, requires 300 feet with a 95% probability.

For purposes of this analysis an accuracy of one city block with 95% probability will be assumed as representative of the requirements for all applications considered.

C. ALTERNATIVE SYSTEMS

The purpose of this study is to evaluate the utility of an integrated location system that would serve the needs of citizen's alarm users and cargo security systems. It is therefore necessary to investigate alternate vehicle locations in order to establish comparative costs, etc. to determine how much vehicle users might be willing to contribute to a citizen's alarm system. The amount of the contribution is established by estimating the least cost alternative.

There are a variety of techniques for automatic vehicle monitoring, several of which have already been implemented. Cost comparisons were made of seven alternative techniques in a previous Aerospace study of automatic vehicle location systems for police patrol operations[5]. The techniques compared in that study, and briefly summarized here, included:

- Radio frequency direct proximity
- Magnetic direct proximity
- Dead reckoning with computer mapping
- Dead reckoning with direct proximity
- LORAN C time differencing
- Pulse trilateration time differencing
- AM phase time differencing

In a radio frequency direct proximity system, signpost transmitters placed at intervals along the roadside continually transmit coded signals containing location data. As a vehicle passes one of these signposts, the signals are received, decoded and, along with a vehicle identification code, retransmitted to the control center via a mobile radio channel.

Magnetic direct proximity techniques involve coded arrays of magnets buried under city streets. Each vehicle contains a device which senses the array as the vehicle passes over it. The location code is then transmitted along with the vehicle code to the control center.

The two dead reckoning techniques evaluated use magnetic compasses and odometers to provide position information relative to a specific location. One of the techniques uses direct proximity signposts to periodically update the dead reckoned position, while the other uses a computer mapping technique to provide continual correction of the dead reckoned position.

The three time differencing techniques involve differences between the times of arrival at a vehicle of radio frequency signals from three or more sources. As shown in Figure IV-1, the locus of points representing a constant distance or time difference between two sources is a hyperbola. Two pairs of sources yield two hyperbolas with the vehicle at their intersection.

The LORAN C method involves use of the existing LORAN navigation transmitters, augmented by additional transmitters to enhance the signal-to-noise ratio in urban areas. The transmitters, which operate in the 100 KHz band, send synchronized pulses from which time-of-arrival differences can be computed. The AM phase technique utilizes the signals of commercial AM radio stations. One station is selected as the master and the other two are synchronized with respect to it. The vehicle unit measures the differences in arrival times by determining phase differences.

The pulse trilateration method operates with a single transmitter and a group of receivers. The signal, which consists of 900 MHz pulses, is received by the vehicle and retransmitted to the fixed receiver sites. The differences in pulse arrival times at the receiver then yields the hyperbolic coordinates of the vehicle.

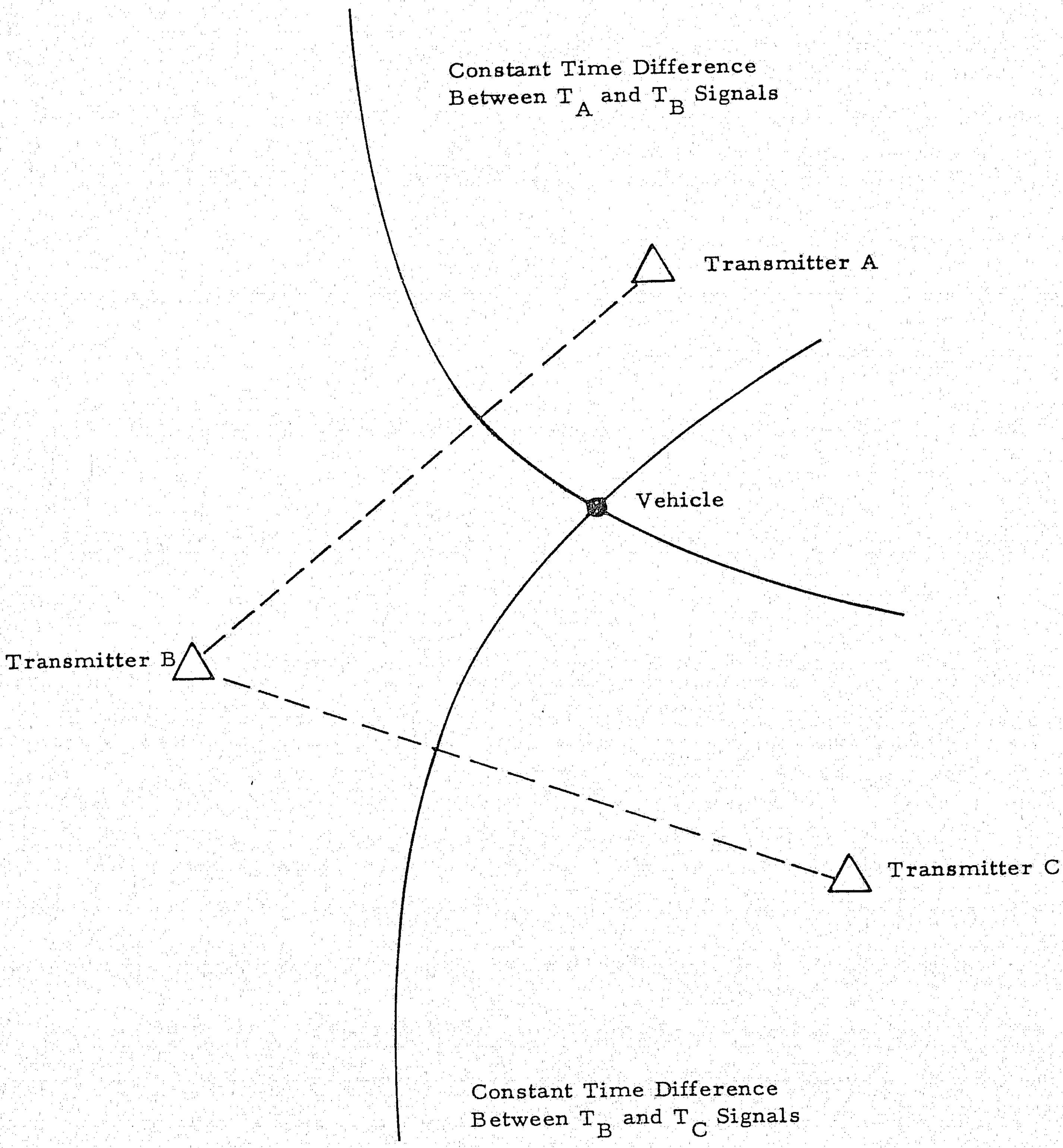


Figure IV-1: HYPERBOLIC LOCATION METHOD

Location accuracy in the direct proximity system depends upon the spacing of the signpost transmitters. With a simple system using a single power level, the location accuracy is equal to the distance between adjacent signposts. However, it is possible to use several power levels which result in several signal overlap areas to create phantom signposts between two actual signposts, using the radiation pattern characteristics of high frequency RF transmitters. Taking boundary effects into account, the ratio of regions to signposts is about 5 to 1. Thus, an RF direct proximity system can attain a location accuracy of one block with one signpost for every five blocks.

The vehicle unit contains a receiver, decoding unit, storage and output registers, and communication interface with the mobile radio transceiver.

The study referred to above[5] compared the seven techniques on an annual cost-per-vehicle basis for a range of vehicle quantities and several values of area covered. Since the study was concerned only with police patrol cars, the maximum number of vehicles considered was 1,000. For this analysis, however, quantities on the order of 10,000 are assumed (police vehicles, buses, taxis, and cargo trucks are included in the vehicle population covered). Therefore, the cost comparison of the police patrol vehicle study was extended to include a larger number of vehicles.

The costs can be separated into three categories: vehicle-related costs which cover the vehicle-borne equipment; area-related costs which cover such equipment as signposts and RF mapping; and fixed costs for the transmitters and the control center computer and display. A single control center was assumed in the patrol car analysis. Table IV-1 reproduces the annual cost estimates for the seven systems.

TABLE IV-1. AUTOMATIC VEHICLE LOCATION SYSTEM COST SUMMARY

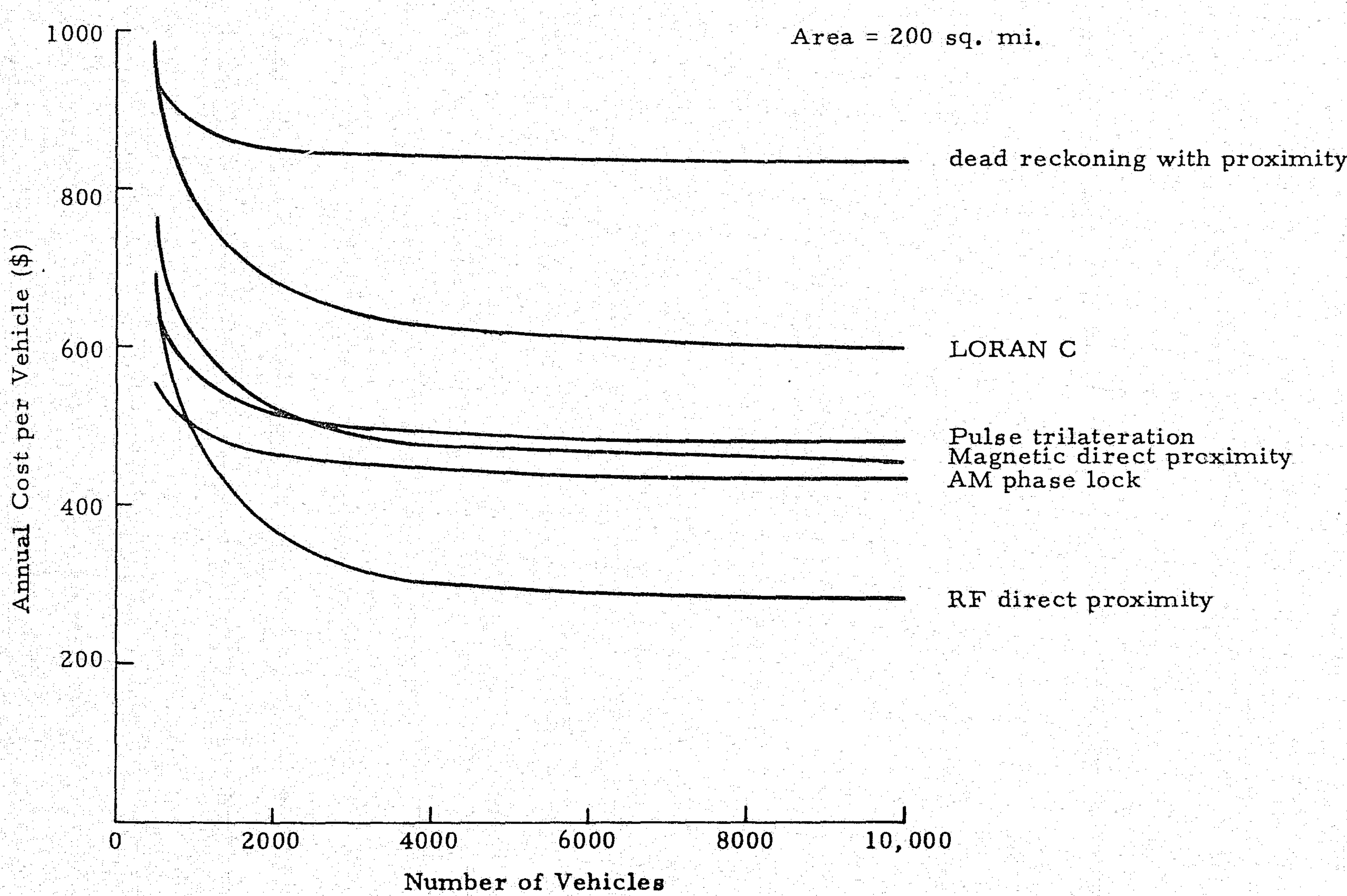
	ANNUAL COSTS		
	Per Sq. Mi.	Per Vehicle	Fixed
Direct proximity (magnetic)	$576	$ 440	$ 47,360
Direct proximity (RF)	$840	$ 260	$ 47,360
Dead reckoning with mapping	---	$1,260	$ 92,000
Dead reckoning with proximity	$ 18	$ 830	$ 47,360
LORAN C	$130	$ 580	$177,360
AM Phase Lock	$ 60	$ 430	$ 51,360
Pulse trilateration	$152*	$ 470	$ 64,360*

*Approximation from straight line fitted to the cost data.

A graph of these data is shown in Figure IV-2 for an area of 200 square miles and vehicle quantities to 10,000. The location accuracy is 300 feet with 95% probability. The dead reckoning system with mapping is not shown as its cost lies wholly above the $1,000 per vehicle value. A fixed cost for the vehicle-borne equipment is assumed with no adjustment for lower unit cost for larger quantities. If a learning curve factor were to be included, it would serve to decrease the cost of each system for high vehicle quantities but the relative positions of the curves would remain the same.

It is evident that the RF proximity technique is the least costly for vehicle quantities above 1,000. This is true because the relatively large area cost is pro-rated over a large number of vehicles, allowing the low vehicle cost to dominate. The AM Phase Lock system is least costly for small vehicle quantities as its fixed costs are relatively low. Similarly, plots for areas of

Figure IV-2: AUTOMATIC VEHICLE LOCATION SYSTEM COST COMPARISON



100 to 400 square miles show the same results with the crossing point between AM phase lock and RF proximity occurring at about 450 vehicles for 100 square miles and 1800 vehicles for 400 square miles. That is, RF proximity is least costly for vehicle quantities larger than these values.

Since the RF proximity system is least costly over the range of parameters pertinent to this analysis, it is selected as the alternative automatic vehicle location concept to be compared with citizen's alarm system.

V. SYSTEM COST ESTIMATES

In developing cost estimates for the citizen alarm and vehicle location systems, the following assumptions were made. Life cycle costs are used, assuming vehicle and personal equipment lifetimes of five years and fixed equipment lifetimes of ten years. For mass produced equipment such as sign-posts and vehicle units, the quantities are assumed to be large enough so that the production learning curves have leveled off. Costs are estimated on an annual basis with no discounting of the future and no inflation factor.

Table V-1 lists the estimated costs for the direct proximity vehicle location systems, taken from an Aerospace report on the use of automatic vehicle monitoring for police patrol.[5] Table V-2 lists the citizen alarm system costs, based upon discussions with the Compu-guard Corporation. A few of the entries require further explanation. The estimated acquisition cost of a vehicle unit assumed for this study is half that given in Reference 5 because of larger number of units involved. The police automatic vehicle monitoring application analysis assumed on the order of 1,000 vehicles, while this study assumes 10,000 vehicles as discussed in the next chapter. Both the RF proximity and citizen alarm systems involve the attachment of units (transmitters and receiver-relays, respectively) to fixed poles such as light standards. The yearly lease cost per unit is estimated to be \$6.[6] The annual line lease cost is \$4 per mile per month or \$48 per mile per year.

The use of the citizen alarm system for vehicle location implies that the relatively complex vehicle unit consisting of a receiver, decoder, and communications interface can be replaced by a rather simple transmitter similar to the personal actuator without the size constraint, using the vehicle power rather than its own self-contained battery, and generating signals continuously (with a specified duty cycle) rather than actuated upon demand. It is estimated that the cost of such a unit manufactured in large quantities would be about the same as that of the personal actuator. It is further assumed that the installation cost would be about $40. Thus the annual cost, assuming a lifetime of five years, is equal to $27 for acquisition and maintenance plus $8 for installation (amortized), or a total of $35.

TABLE V-1.

RF Proximity Automatic Vehicle Monitoring System

Cost Estimates

	Unit Cost	Annual Cost
Vehicle Unit (5 yr. lifetime)		
Acquisition	$400	$ 80
Installation	100	20
Maintenance		40
TOTAL		$140
Signpost (10 yr. lifetime)		
Acquisition (installed)	70	7
Maintenance		7
Post Lease		6
TOTAL		$20

TABLE V-2.

Citizen Alarm System Cost Estimates

	Unit Cost	Annual Cost
Primary receiver-relay (10 yr. lifetime)		
Acquisition	$180	$18
Installation	45	5
Maintenance		59
Post Lease		6
TOTAL		$88
Secondary receiver-relay (10 yr. lifetime)		
Acquisition	$330	$33
Installation	120	12
Maintenance		59
Post Lease		6
TOTAL		$110
Actuator (5 yr. lifetime)		
Acquisition	$73	$15
Maintenance		12
TOTAL		$27
Annual Line Lease		
Cost per mile		$48
Control Center (10 yr. lifetime)		
Processor & Display	$23,000	$2,300
Installation	1,000	100
Maintenance		15,000*
TOTAL		$17,400

*Annual cost of maintenance contract

VI. COST EFFECTIVENESS ANALYSIS

The first step in the cost/effectiveness comparison of shared and unshared utilizations of the citizen alarm system is the determination of the optimal deployment of the system in an unshared mode, which allows a basis of comparison.

The measure of effectiveness used in the analysis is the expected cost per apprehension. This measure reflects the capability of the system to allow rapid police response to a violent criminal act, the coverage of the system and its cost. The cost per apprehension is used to compare the effectiveness of alternative deployments, and to select an "optimal" deployment.

A. CITIZEN'S ALARM SYSTEM DEPLOYMENT

The city of Chicago was selected for the base case as it represents a fairly typical urban environment and a large amount of detailed crime and population data was available for the city from a study performed by the Operations Research Task Force of the Chicago Police Department during 1968-71.[7] This report contains the following data by police district, of which there are twenty-one:

- Population
- Area
- Number of major crimes by category (rape, robbery, etc.)
- Number of police patrol cars

As stated in Chapter III, the primary purpose of the citizen alarm system is to enhance the chances of the police apprehending a criminal during (or immediately subsequent to) the conduct of a serious crime against a person, i.e., rape, robbery, or assault. The timeliness of arrival by police in response to an alarm is critical. It is assumed for purposes of this analysis that an alarm signal is sent at the initiation of the crime and the actuators work perfectly. The crime duration is assumed to be a statistical parameter, with equal probability for each value between two specified limits. That is, the probability density function for crime duration is:

$$P_{c(t)} = \frac{1}{d_2 - d_1} \qquad d_1 \leq t \leq d_2$$

$$P_c(t) = 0 \qquad \text{Otherwise}$$

where

d_1 = minimum duration

d_2 = maximum duration

Very little substantive data exists on the duration of crimes. One of the few studies in that area was done by Feeney and Weir[8], who interviewed 93 robbery victims to obtain estimates of the duration of the crimes. Of the 65 who were able to estimate the time, two-thirds stated that the duration was less than three minutes. For this analysis, it will be conservatively assumed that the duration for violent crimes is from 0 to 3 minutes.

The response time of the police patrol vehicle is also a statistical parameter, depending upon the vehicle speed, street distance between the vehicle and the alarm signal location, communication time delay, and search time. Assuming that arrival by police during the execution of a crime is tantamount to apprehension of the criminal, the probability of apprehension can be obtained from the crime duration and police response time probability distributions. Mathematically, this is expressed as:

$$P_A = \int_{t=0}^{\infty} \int_{x=0}^{t} P_R(x)dx \quad P_c(t)dt \qquad (1)$$

where

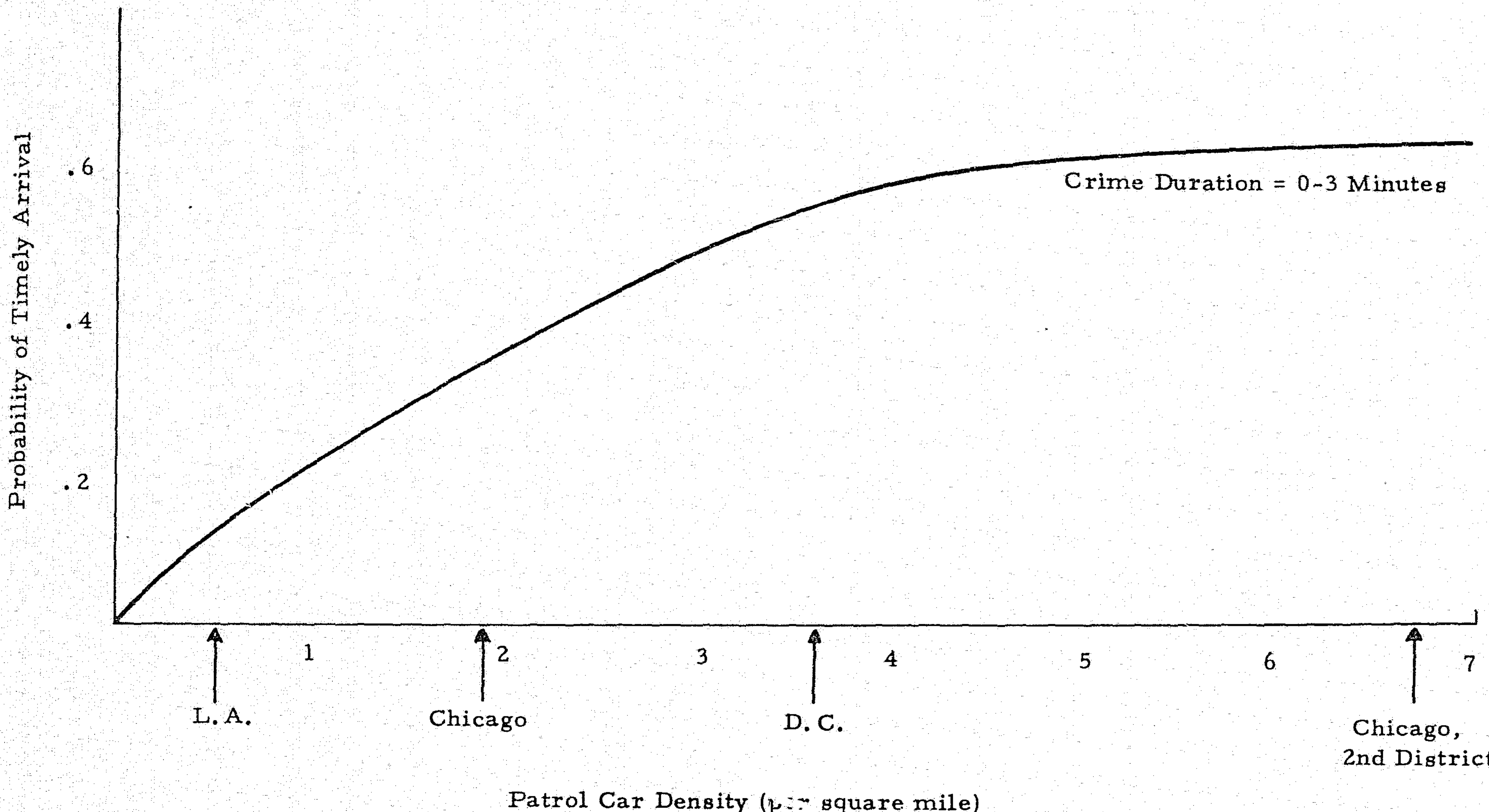
P_A = probability of apprehension (or timely arrival)

$P_c(t)dt$ = probability crime is of duration t to t+dt

$P_R(x)dx$ = probability police response time is between x and x+dx

Figure VI-1 depicts the relationship between the probability of apprehension and the density of patrol vehicles. The average speed is assumed to be 30 miles per hour (probably achievable using flashing lights and sirens).

Figure VI-1: EFFECT OF PATROL CAR DENSITY ON TIMELY ARRIVAL PROBABILITY



The search time after the patrol vehicle reaches the scene is assumed to be about 30 seconds. The utilization rate (average percentage of time a patrol car is servicing calls) is 40%.[7] No dispatch delay time is assumed since these are urgent response calls. The curve is derived from a computer program developed by The Aerospace Corporation[9] based upon an extension of a model developed by R. C. Larson.[10]

The population base for the system is assumed to be residents of age 18 and over. The proportion of the eligible population that would subscribe to the service is questionable at this time. According to a survey[11] of households in a high crime area, about 34% would subscribe at an annual cost of $50 or more, with another 3% joining if the price were between $26 and $49. Approximately one-third of these households would obtain actuators for their children at a one-time cost of $20 each. Responses to other proposed actuator costs were not given nor were the ages of the respondent family members.

It is likely that the number of persons in the system will depend upon a number of factors including the demonstrated degree of effectiveness of the system, once deployed. It is estimated for the purposes of this study that 10% of those eligible would subscribe over the long range. The sensitivity of the cost/effectiveness results to this parameter is discussed in the latter part of this chapter.

The number of crimes for which the CAS is applicable depends upon the crime rate in the area of application, the population with CAS actuators, the probability of actuation by a victim who has a CAS device, and the proportion of violent crimes that occur outdoors (in the current scenario). The expected number of apprehensions (E_A) per year in a given region resulting from CAS use is expressed by:

$$E_A = P_A E_{NC}$$

or

$$E_A = P_A N_p P_u R_{vc} P_{co} \qquad (2)$$

where

E_{NC} = expected number of violent crimes per year for which CAS is used

N_p = number of persons in the region age 18 and older

P_u = proportion of eligible population with actuators

R_{vc} = violent victimization rate (crimes per year per person)

P_{co} = probability crime occurs outdoors

The annual cost of the system is given by:

$$C_{CAS} = C_{PR} N_{PR} + C_{SR} N_{SR} + C_L + C_A N_A + C_{CC} \qquad (3)$$

C_{PR} = annual cost per primary receiver

N_{PR} = number of primary receivers

C_{SR} = annual cost per secondary receiver

N_{SR} = number of secondary receivers

C_L = annual cost of leased lines

C_A = annual cost of an actuator

N_A = number of actuators

C_{CC} = annual cost of the control center

The number of actuators is a function of the eligible population and the proportion subscribing to the system.

$$N_A = N_p P_u \qquad (4)$$

Further, since the population age 18 and over is about 68% of the total population, Equation (4) becomes:

$$N_A = 0.68NP_u \tag{5}$$

where N is the total population.

As noted earlier, there are assumed to be one primary receiver-relay per block, 144 blocks per square mile, and ten primary receiver-relays for each secondary. Further, one control center is assumed per district.

To determine the leased line mileage from the secondary receiver-relay to the control center, consider an area one mile square with the control center in the center. There are 144 primary receiver-relays in the square and about 15 secondaries. By placing these secondaries judiciously a total line distance (following city streets) of 54 blocks or 4.5 miles can be achieved. The annual line cost for the one square mile area is then 4.5 times the annual lease cost per mile, C_{AL}.

To approximate the relationship between area and line mileage, an empirical approach was taken. Squares of 2, 4, and 8 receivers per side were considered. The total distances from the receivers to the center of each square are 4, 32, and 256 units, with a unit representing the distance between adjacent receivers. The total number of receivers for the three cases are 4, 16, and 64 units. Therefore, the average distance per receiver is 1, 2, and 4 units, respectively. This can be generalized to the rule that the average line distance per receiver-relay doubles for each quadrupling of the area. That is, this average distance is proportional to the square root of the area. Since the number of receiver-relays varies directly with area, A, the total line mileage varies as $A^{3/2}$. The line cost, C_L, for an area of size A is then the product of the line cost for an area of one square mile (4.5 C_{AL}) and the proportionality factor, $A^{3/2}$. Combining terms, we have:

$$C_L = 4.5\ A^{3/2}\ C_{AL} \tag{6}$$

Equation 3 for the annual CAS cost for a district of area A and population N then becomes:

$$C_{CAS} = 144A\ (C_{PR} + 0.1\ C_{SR}) + 0.68\ P_u NC_A + 4.5A^{3/2}\ C_{AL} + C_{CC} \tag{7}$$

Table VI-1 lists the pertinent statistics for Chicago by police district, taken from Reference 7. District 1, which is primarily a business district, is not included because with a resident population of 14,000 and approximately 100,000 persons during the daytime, its statistics are greatly distorted. The crime rates, which average 9.54 per 1000 residents for the city, represent reported violent crimes for 1968. It is felt to be more realistic however, to use victimization rates; that is, estimates of crimes experienced by citizens from interviews of random samples of Chicago citizens. For 1973, the number of violent crime victimizations for Chicago citizens age 12 or over was 101,892 or 42.0 per 1000 residents, as reported in the U.S. Department of Justice Report on criminal victimization in the five largest U.S. cities.[12] Approximately 68% of the U.S. residents are age 18 and over. Multiplying this factor by the ratio 42.0/9.54 yields the multiplicative factor 3.0 which is used to adjust the number of 1968 reported violent crimes for each district in Table V-1 to obtain 1973 victimizations for persons 18 years and older. This procedure implicitly assumes the proportion of 1973 victimization rates to 1968 crime rates are constant over all districts. With no evidence to the contrary, this is the most reasonable assumption to make.

The value of the probability of the crime occurring outdoors, P_{co}, is estimated at 60%, based upon victimization data for Chicago.[12] As noted above, it is estimated that 10% of the eligible persons utilize CAS.

Table VI-1. CRIME STATISTICS FOR CHICAGO BY DISTRICT, 1968

District	Violent Crimes	Population (1000's)	Crime Rate (per 1000 resdts.)	Area (sq. mi.)	Patrol Cars	Patrol Car Density (cars/sq. mi.)	Population Density (1000s/sq. mi.
1	756	14	54.00	~1	10	~10	~14
2	5014	155	32.35	4.3	29	6.7	35.94
3	2272	173	13.13	5.5	27	4.9	31.33
4	566	171	3.31	26.3	15	0.6	6.50
5	844	173	4.88	20.0	17	0.8	8.63
6	636	162	3.93	16.2	15	0.9	9.98
7	2516	155	16.23	6.5	27	4.1	23.72
8	395	234	1.69	23.6	15	0.6	9.91
9	639	175	3.65	13.2	20	0.7	13.29
10	2690	170	15.82	7.2	24	3.3	23.59
11	3393	124	27.36	4.8	25	5.3	26.11
12	2280	126	18.10	6.3	16	2.5	20.06
13	2202	141	15.62	5.2	23	4.5	27.36
14	771	181	4.26	7.8	20	2.6	23.35
15	1001	197	5.08	11.9	18	1.5	16.49
16	201	206	0.98	28.4	11	0.4	7.25
17	279	170	1.64	10.5	12	1.1	16.13
18	2506	133	18.84	4.2	22	5.2	31.29
19	979	198	4.94	5.7	25	4.4	34.72
20	1149	289	3.98	11.6	30	2.6	24.83
21	2074	129	16.08	5.0	23	4.6	25.81
TOTAL	33,190	3480	9.54	225	425	1.9	15.47

Applying the 1973 victimization rate factor 3.0 and the values given above for P_{co} and P_u, yields the following relationship for expected number of apprehensions:

$$E_A = 0.18\, N_{vc} P_A \qquad (8)$$

where N_{vc} is the number of reported violent crimes.

The probability of timely arrival, P_A, for each district, based upon the patrol car density, is obtained from Figure VI-1. These probabilities are presented in Table VI-2 along with the expected number of apprehensions per district computed from Equation 8, the cost per district based on Equation 7, and the cost per apprehension per district. The total annual number of apprehensions attributed to the CAS, 3040, represents about 3% of the number of violent crimes committed in the city in one year.

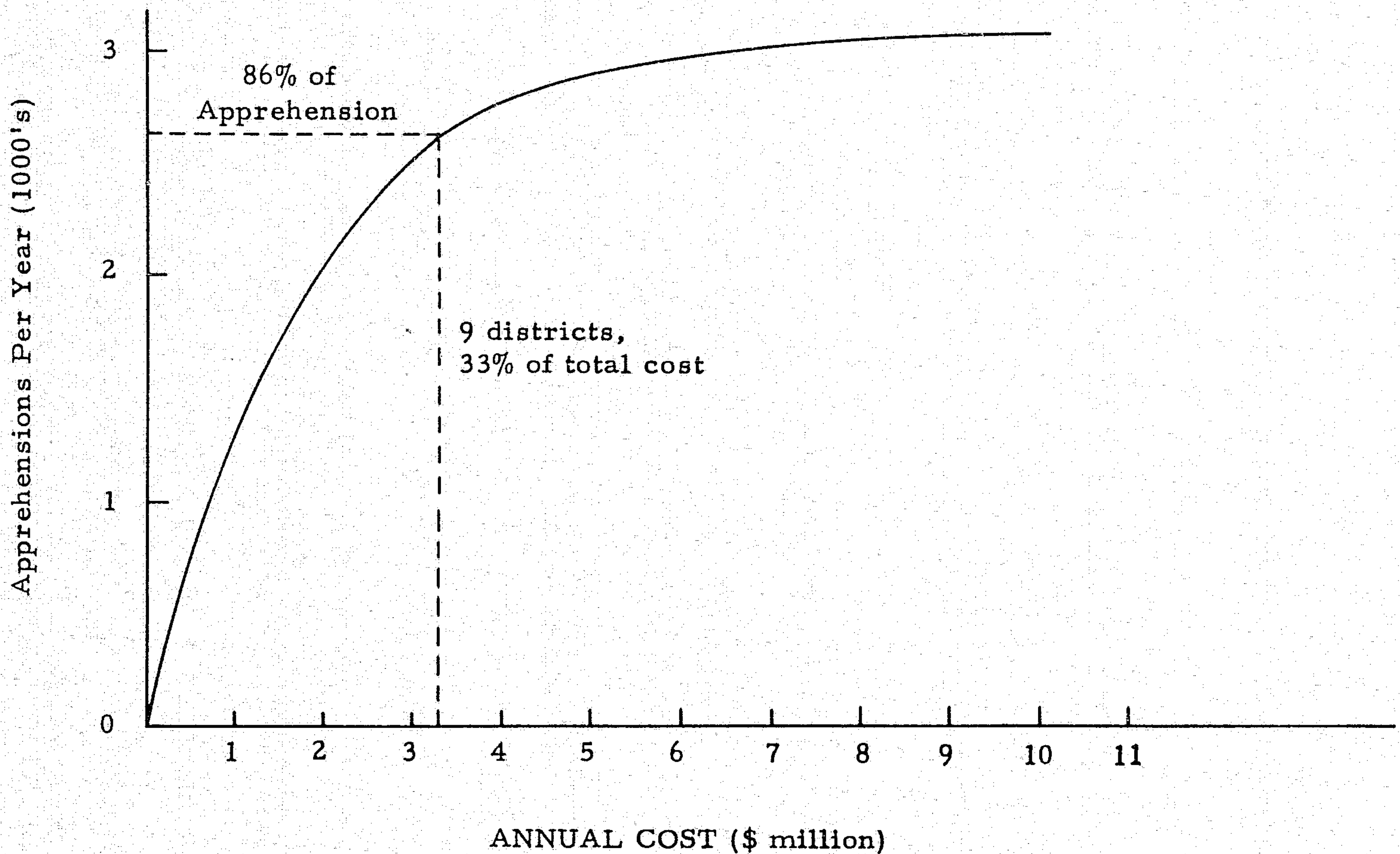
Taking the districts in order of increasing cost per apprehension, a cumulative curve of cost expended vs. number of apprehensions can be developed as in Figure VI-2. It is clear from this curve that the initial districts yield a relatively high return for the money and as more districts are included the marginal return decreases. There are several factors that combine to cause this phenomenon. First, certain districts have much higher crime rates than others. Generally, these same districts have much higher population densities resulting in lower cost per person since receiver-relay costs are functions of areas covered. In addition, these high crime districts generally have more patrol cars per square mile, which results in a quicker response time, thereby enhancing the probability of apprehension. For example, of the ten highest crime rate districts in Chicago, eight are also in the group of ten highest population density districts and all of the ten highest patrol car density districts are in the group of the ten highest population density districts.

Table VI-2. COST AND APPREHENSION STATISTICS BY DISTRICT FOR CHICAGO

District	Probability of Timely Arrival	Number of Apprehensions	CAS Cost	Cost per Apprehension	Rank *
2	.65	586.6	$ 365,200	$ 623	1
3	.60	245.4	416,200	1,696	7
4	.15	15.3	735,400	48,065	18
5	.19	28.9	639,400	22,125	14
6	.20	22.9	560,000	24,454	15
7	.58	262.7	398,000	1,515	5
8	.15	8.9	808,200	90,800	19
9	.17	19.6	537,200	27,400	16
10	.50	242.1	436,300	1,802	8
11	.61	372.6	315,800	848	2
12	.46	188.8	342,000	1,811	9
13	.58	230.0	353,000	1,535	6
14	.45	62.9	465,600	7,450	11
15	.30	54.1	557,600	10,307	13
16	.10	3.6	833,200	231,440	20
17	.21	10.5	486,600	46,340	17
18	.61	275.2	323,300	1,174	3
19	.57	100.4	465,100	4,630	10
20	.45	93.1	721,900	7,754	12
21	.58	216.5	327,900	1,515	4
TOTAL		3,039.7	$ 10,087,900	$ 3,319	

* According to cost per apprehension

FIGURE VI-2: CAS COST/EFFECTIVENESS FOR CHICAGO



Using complete coverage of the city as a basis, approximately 86% of the apprehensions are made in the nine highest crime rate districts which represent 33% of the total expenditures. This point represents a knee of the curve as the cost per apprehension for the tenth ranked district (number 19) is more than double that of the ninth ranked district (number 12). Therefore, it appears that the most cost-effective deployment of a citizen alarm system in Chicago would be to cover only the nine highest crime rate districts.

It may be of interest to note that of the $10 million annual cost for the fully-deployed system, 63% is for the actuators, 32% for the receiver-relays, 2% for the communication lines, and 3% for the control center equipment. For the nine-district deployment ($3.3 million annual cost), the percentages are 73% for actuators, 21% for receiver-relays, 1% for communication lines, and 5% for control center equipment.

B. COST ANALYSIS OF AN INTEGRATED SYSTEM

Integration of the citizen alarm system with a vehicle monitoring system implies that the system must be deployed throughout the whole city since the vehicles, which may include buses, taxis, trucks and police patrol cars, can be expected to travel in all parts of the city. The contribution by the vehicle users to the cost of the system is assumed to be such that the total cost to the vehicle users is no greater than the total cost of the least cost automatic vehicle monitoring system alternative.

In order to determine the least cost alternative, a typical vehicle profile was assumed for Chicago. Recall from Chapter IV that probable users of an automatic vehicle monitoring system included buses, taxis, police patrol vehicles, and local commercial trucks. Table VI-3 lists the estimated number of vehicles in each category for Chicago.

TABLE VI-3.

Vehicle Quantities for Chicago

	Number	Data Source
Police Patrol Vehicles	500	Reference 7
Buses	2,500	Reference 13
Taxis (radio-dispatched)	2,000	See Below
Trucks	5,000	Reference 14
TOTAL	10,000	

The total number of taxi licenses for Chicago is 4,600.[15] It is estimated that approximately half of these are radio dispatched. The estimate for local commercial trucks was extrapolated from data taken from the Motor Vehicle Manufacturer's Association Publication, "1974 Motor Truck Facts," which listed truck registration by state and by application -- construction, wholesale/

retail, utilities, services, for-hire, personal, and other. In addition, the percentages of trucks in each category that belong to fleets of twenty or more was given. Since truck registration was not cited by city except for the District of Columbia, the Washington, DC figures were used and extrapolated for Chicago. Wholesale/retail trucks were considered as candidates for cargo security systems since they are most likely to have cargo stolen. Further, only those trucks in fleets were considered since fleet owners are most likely to be able to afford a cargo security system. There are 3,000 wholesale/retail trucks registered in the District of Columbia, of which approximately 40% are estimated to be in fleets of twenty or more. Assuming the same number of commercial trucks per capita, this results in about 5,000 commercial fleet trucks for Chicago.

It is recognized that these estimates of fleet vehicle quantities are very rough, especially for taxis and trucks. However, exactness is not critical to the forthcoming analysis. In fact, as will be shown, doubling the number of vehicles in the system does not alter the conclusions.

Referring back to Chapter IV, recall that the least costly automatic vehicle monitoring system for more than 1,000 users in a city the size of Chicago is the RF direct proximity system. The cost elements for this system include signposts, vehicle units, and control center equipment. If the vehicle users are to utilize the citizen alarm system rather than implement their own direct proximity system, they will realize a savings by having cheaper vehicle units ($35 per year for CAS vs $140 per year for direct proximity) and by no longer requiring the RF signposts. The control center costs are assumed to remain the same. The total signpost cost for the city of Chicago is taken to be $130,000 per year. This is derived by assuming 144 blocks per square mile, 225 square miles of area, one signpost every five blocks (see Chapter IV), and $20 per signpost per year (see Chap. V).

This annual savings of $130,000 plus $105 per vehicle can then be contributed to the citizen alarm system as a fee for use of the system. This has the effect of maintaining the same annual cost for the vehicle users and reducing the cost to the citizen alarm users. If the fee were higher than this, the vehicle users could implement their own system and save money. Therefore, this amount represents the maximum reasonable fee for use of the CAS. Table VI-4 presents the breakdown of costs in calculating the fee. The question is then: Does the resulting reduction in cost make the citizen alarm system sufficiently cost effective to warrant deployment throughout the city?

TABLE VI-4.

Vehicle/Citizen Cost Sharing

Number of Vehicles	10,000	
Differential Cost Per Vehicle	$105	
Total Vehicle Cost Difference		$1,050,000
Signpost Cost		130,000
TOTAL ANNUAL FEE		$1,180,000

As presented in Table VI-2, the total annual cost for a citizen's alarm system deployed throughout Chicago would be $10,087,900. The costs to the citizen alarm system with and without sharing by vehicle users are given on Table VI-5, along with the results for the nine-district deployment discussed above.

TABLE VI-5.

CAS Cost Comparison, Chicago

	Without Sharing		With Sharing
	9 districts	20 districts	20 districts
Annual Cost to Citizens	$3,277,700	$10,087,900	$8,907,800
No. of Persons Covered	88,800	235,700	235,700
Annual Cost Per Person	$36.90	$42.80	$37.80
No. of Apprehensions Per Year	2,620	3,040	3,040
Cost Per Apprehension	$ 1,250	$ 3,320	$ 2,930

Note that the cost per apprehension for the nine districts is less than half that for all 20 districts of the city even when the system is shared with as many as 10,000 vehicles. It is concluded that deploying the system throughout the city and sharing it with vehicle users is not cost-effective compared with the option of deploying the system only in the high crime, high density districts.

It is, of course, possible that other factors (e.g., political) may impact on the decision of where to deploy a CAS resulting in deployment throughout a city. If such is the case, two operational aspects of sharing the system with vehicle users should be considered. A brief discussion of these operational problem areas is presented in the following chapter.

C. SENSITIVITY ANALYSES

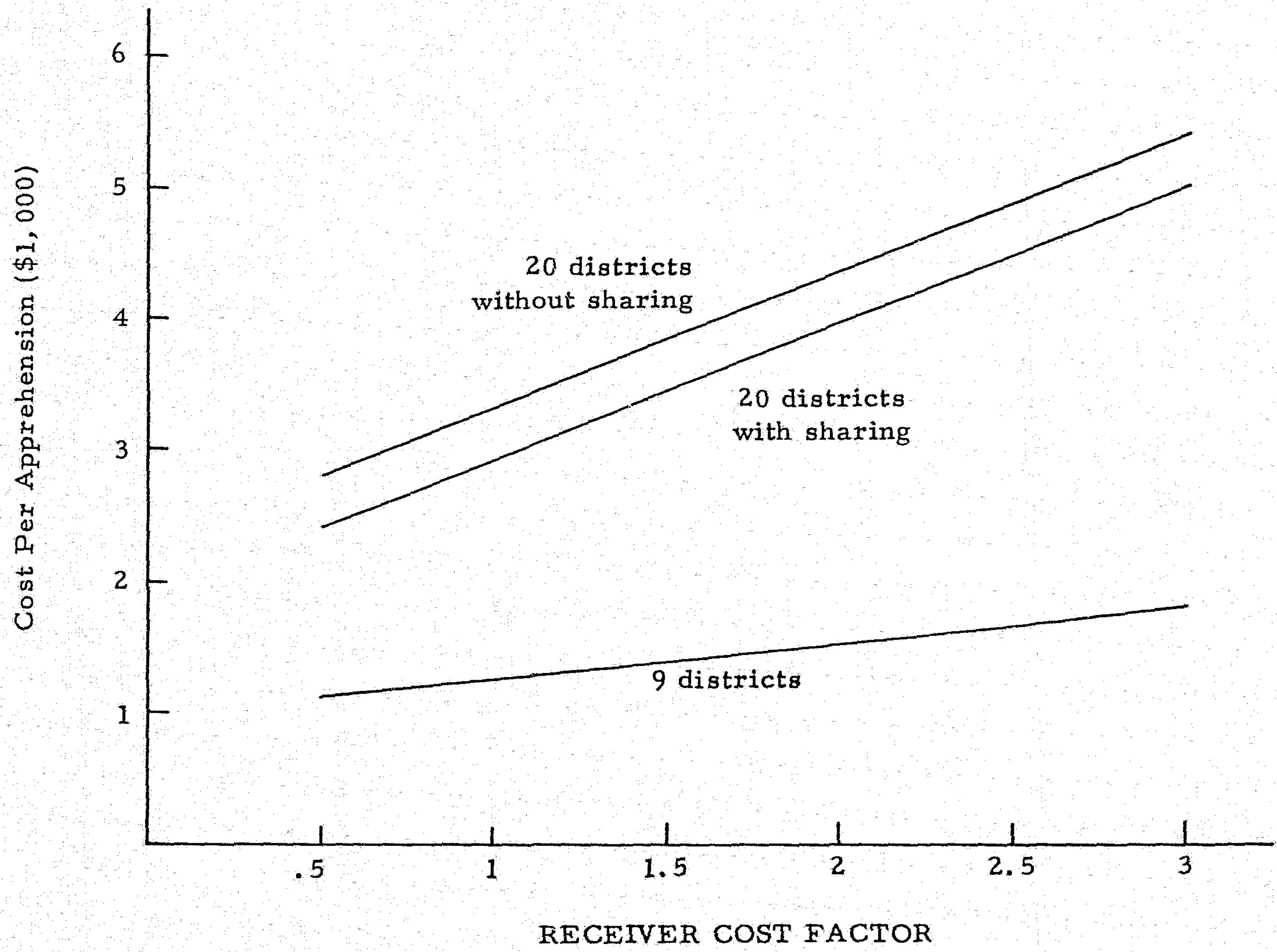
This section treats the sensitivity of the cost/effectiveness results to variations in several of the input parameters including receiver-relay cost, actuator cost, percentage of eligible population using the citizen alarm system and number of vehicles sharing the system.

Figure VI-3 presents the cost per apprehension as a function of the primary and secondary receiver-relay costs for the two alternative deployments with and without vehicle sharing. The absissa is in terms of a cost factor with 1 representing the costs estimates used in this report, 2 representing a doubling of primary and secondary receiver-relay costs, etc. It is evident that varying the receiver-relay cost does not affect the conclusion that system deployment over nine high crime districts is significantly more cost/effective than deployment throughout the city, even when shared with 10,000 vehicles. In fact, as the receiver-relay cost increases the cost/effectiveness differential also increases. This is true because the lower crime districts are also generally districts with lower population densities resulting in more receiver-relays per capita and per violent crime. Increasing the cost of the receiver-relays then increases the cost per apprehension more in the 20-district deployment than in the 9-district deployment.

Next, the sensitivity of the results to the annual cost per actuator is investigated. This variable is involved in two ways. First, the actuator cost is part of the total system cost given by Equation 7. Also, the cost contribution of the vehicle users as shown in Table VI-4 is a function of the actuator cost under the assumption that cost of the vehicle-borne signalling device would be about the same as the personal alarm device. The contribution, C_C, is:

$$C_C = N_V (140 - C_A) + C_S \qquad (9)$$

FIGURE VI-3: SENSITIVITY OF CAS COST/EFFECTIVENESS TO RECEIVER COST



where N_V = number of vehicles

C_A = annual cost per actuator

C_S = cost of the direct proximity signposts

Therefore, as the actuator cost is increased, the contribution by the vehicle users decreases. This is the reason for the slight difference in slope of the two 20-district curves in Figure VI-4. The difference in the slopes between the 20-district and 9-district curves is because the number of apprehensions per person covered (or per actuator) is much higher in the latter case, or, conversely, the number of actuators per apprehension is lower.

The percentage of eligible citizens who elect to subscribe to the system affects both system cost and effectiveness. The relationship between effectiveness and this percentage is shown in Figure VI-5. The curves for the different cases have essentially the same shape, with the slope flattening out as the percentage increases. With a small number of persons in the system, the allocation of the fixed cost of the receivers results in higher cost per person. However, the crime rate and therefore the number of apprehensions per person remains the same, increasing the cost per apprehension. As the percentage of users increases, the fixed costs are allocated over more people, so that the total annual cost per person approaches the actuator cost.

Varying the number of vehicles sharing the system increases the contribution by these users to the total system costs, as given by Equation 9. The plot of system cost/effectiveness as a function of the number of vehicles is shown in Figure VI-6. It is evident from the graph that even for as large a quantity of vehicles as 30,000, the alternative of covering all 20 districts with the citizen alarm system and sharing with vehicles results in a much higher cost per apprehension than covering only the nine high crime rate districts.

FIGURE VI-4: SENSITIVITY OF CAS COST/EFFECTIVENESS TO THE ACTUATOR COST

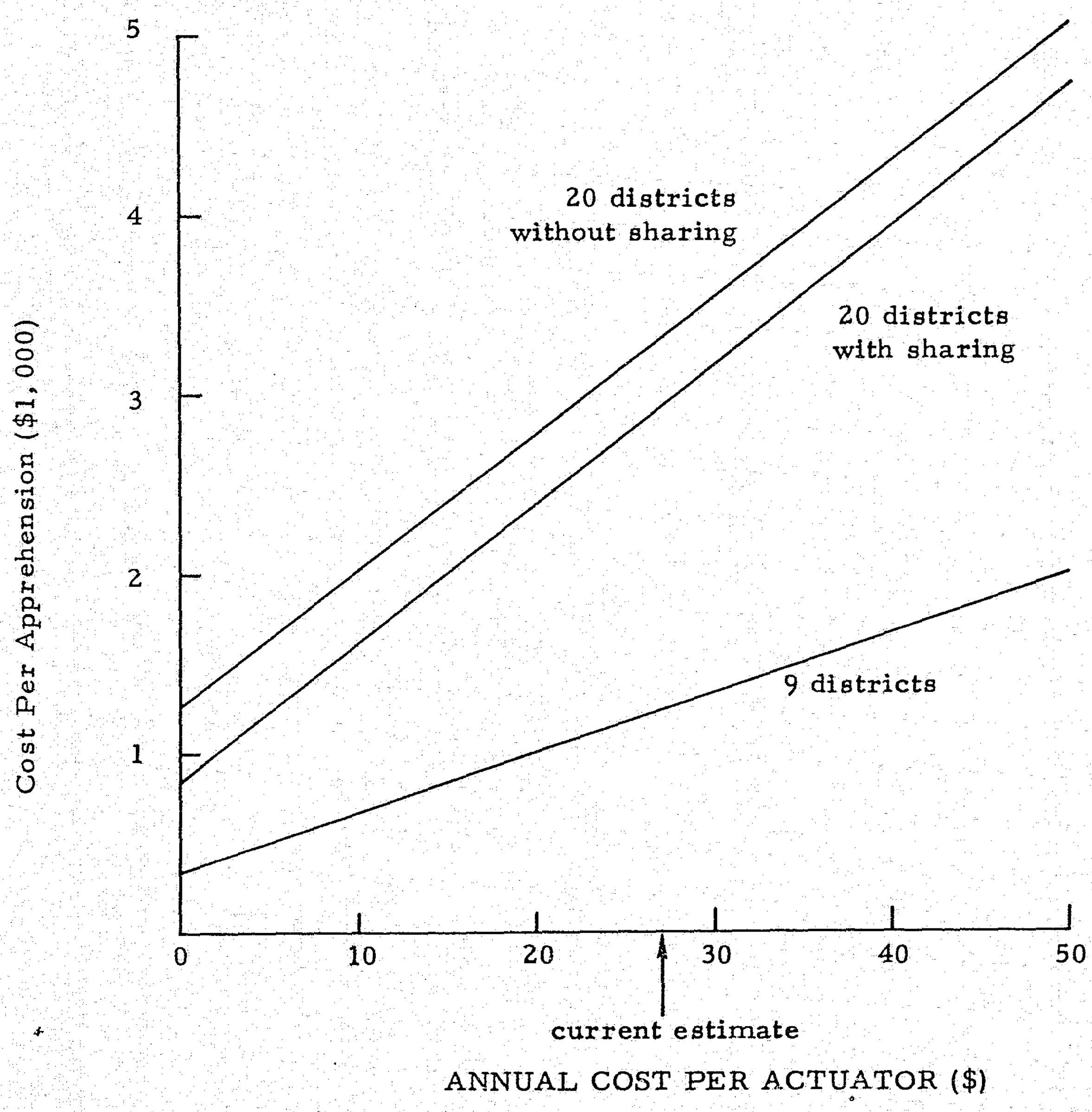
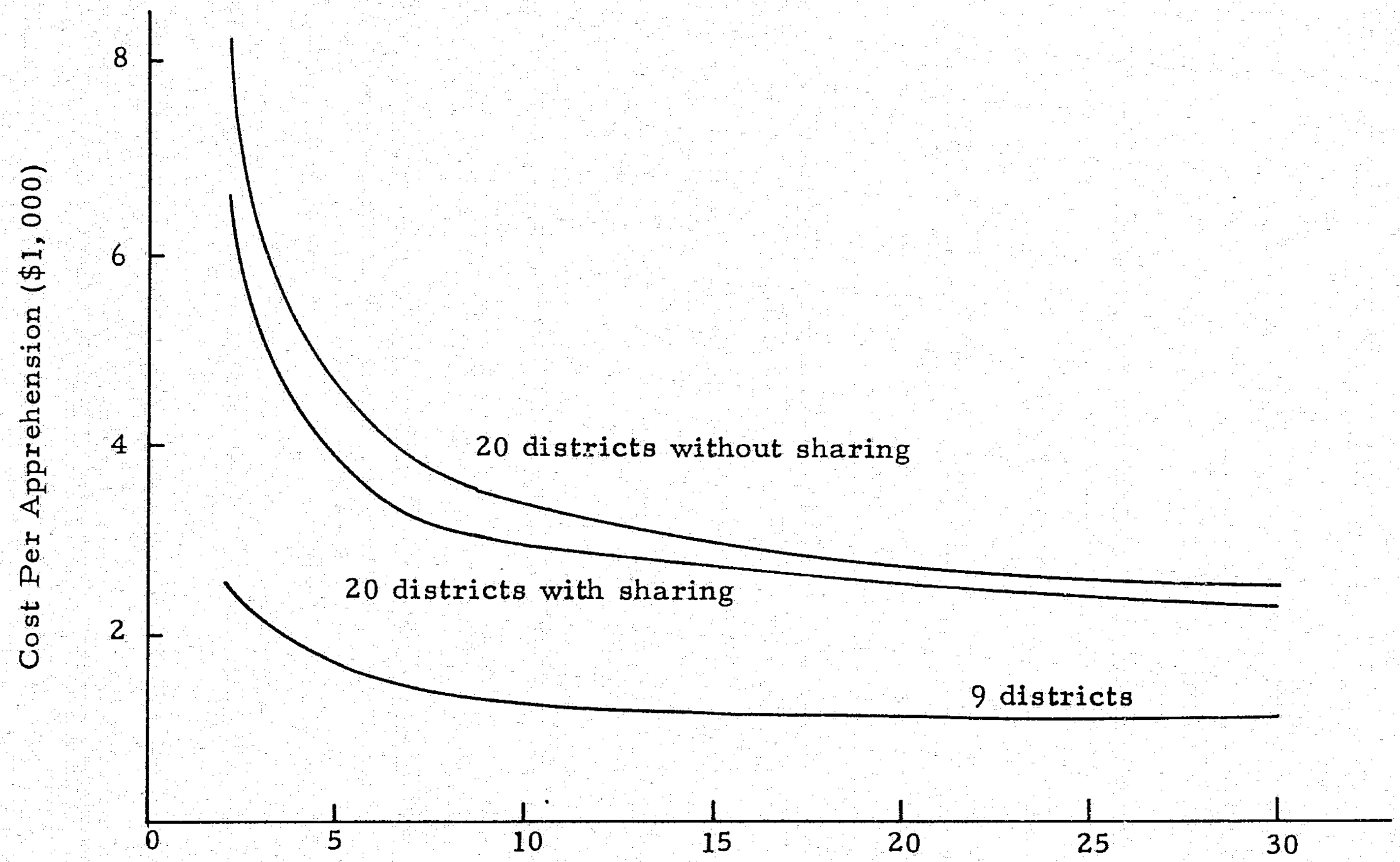
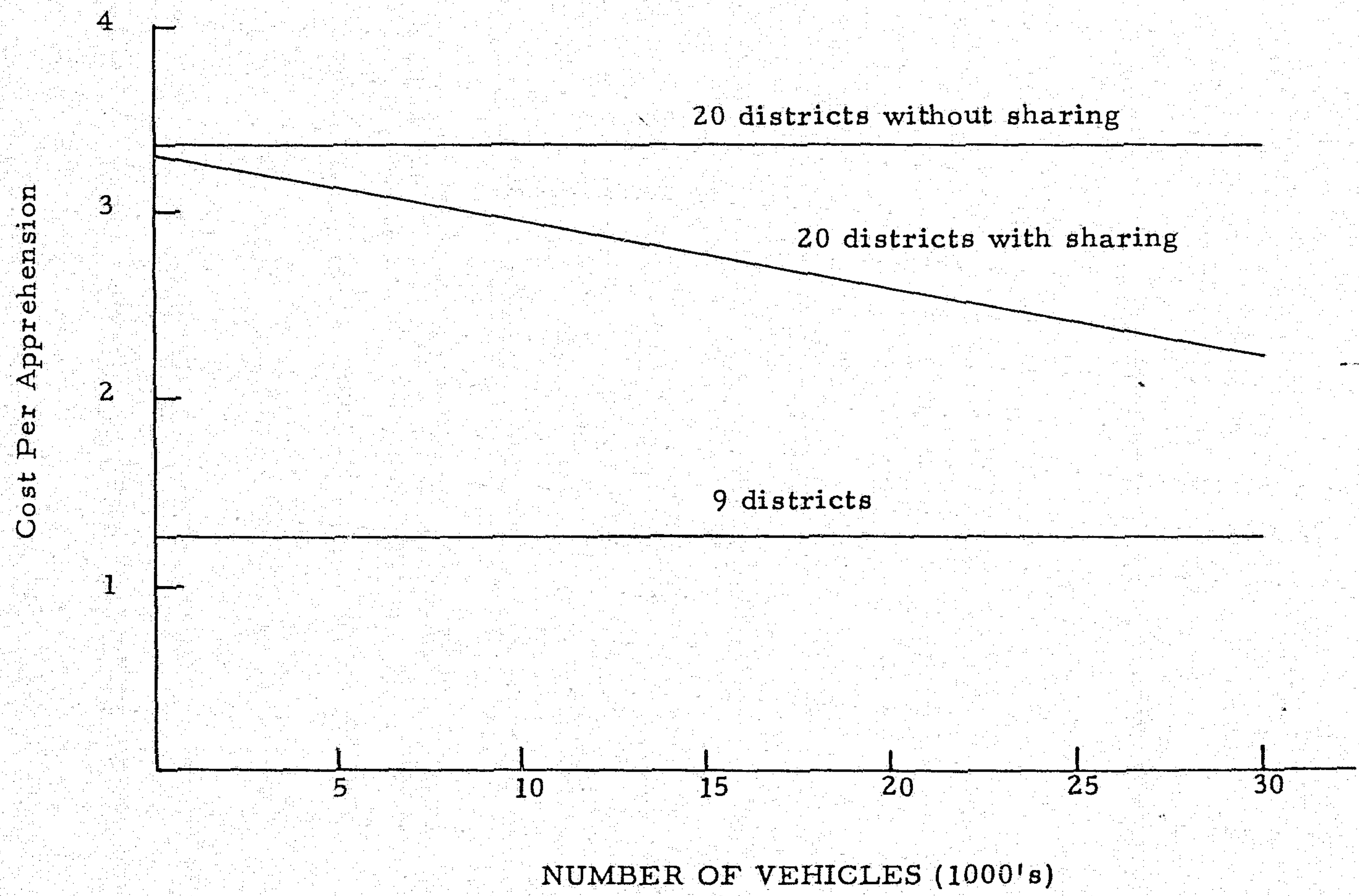


FIGURE VI-5: SENSITIVITY OF CAS COST/EFFECTIVENESS TO PERCENTAGE OF ELIGIBLE POPULATION IN THE SYSTEM



PERCENTAGE OF ELIGIBLE POPULATION USING CAS

FIGURE VI-6: SENSITIVITY OF CAS COST/EFFECTIVENESS TO NUMBER OF VEHICLES



The effectiveness of the citizen alarm system depends upon the ability and desire of the participants to properly utilize it. If people forget to carry the actuator or are afraid or unable to actuate it at the appropriate time, the effectiveness will be degraded. Similarly, if the police do not respond as quickly as possible due to saturation by false alarms or other reasons, or if the average crime duration is significantly shorter than the 1.5 minutes assumed, the hypothesized apprehension rate will not be attained. If for any of these reasons the system proves a fraction f as effective as hypothesized in the analysis, the cost per apprehension will be 1/f times as much as shown. Such a change would not affect the comparison between the three cases, however, since it only represents a shift in the cost-per-apprehension scale.

Because of the availability of detailed crime and law enforcement statistics, Chicago was chosen for the analysis. However, it is believed that the characteristics that yield the great differences in expected cost per apprehension between city districts exist in most large cities in this country. For example, it has been shown[16] that approximately 25% of the violent crimes occur in an area containing about 10% of the population of Washington, DC. As in Chicago, the highest crime rate areas of Washington also have the highest population density.

VII. ANALYSIS OF INTEGRATED OPERATIONS

In addition to cost effectiveness considerations of sharing the citizen alarm system with vehicles, there are several operational problems to be resolved if vehicles are to utilize the system. This chapter briefly addresses two of the most important of these problems to provide an indication of their scopes. Technical solutions are beyond the scope of this study, however.

A. CONTENTION

First, the problem of contention, or mutual interference of two or more vehicles transmitting to a single receiver-relay, is addressed. Consider a vehicle within transmission range of a receiver-relay. Its signal will be interfered with if another vehicle is also within range during the same time period and if the signals overlap in time.

Vehicle location signals are assumed to be transmitted according to a specified duty cycle. Assume a transmission with a duration of t seconds occurring every x seconds. Contention will occur between two vehicles if any part of the signals overlap. Thus, referring to Figure VII-1, the second vehicle will interfere with the first if the transmission of the second begins at any time from t seconds before the first began, $t_o - t$, to the end of the first transmission, $t_o + t$. Assuming the transmission times are random and the duty cycles the same, the probability of contention is simply:

$$2t/x \tag{1}$$

The ratio t/x is the duty cycle d.

If there are n vehicles in addition to a given vehicle, the probability that at least one contends with it is:

$$P(C|n) = 1 - (1 - 2d)^n \tag{2}$$

Assume one can define a region containing the receiver-relay in question so that there is an equal probability of a vehicle being within any small cell within the region. Then the probability of n vehicles being within the transmission range is given by the Poisson Distribution:

$$P(n) = \frac{\lambda^n}{n!} e^{-\lambda} \tag{3}$$

where

λ = average number of vehicles in the transmission region.

Figure VII-1: CONTENTION DIAGRAM

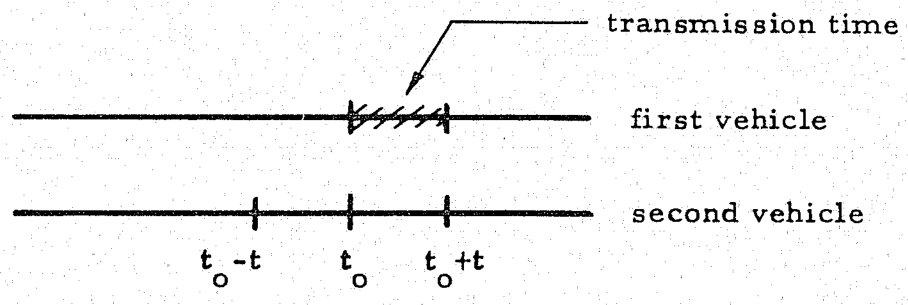
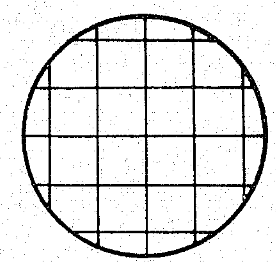
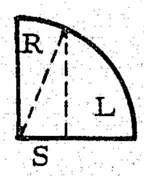


Figure VII-2: CIRCULAR TRANSMISSION PATTERN COVERAGE



a) Street Pattern



b) Street Length in one Quarter

The probability that a given vehicle's signal is interfered with is:

$$P_c = \sum_{n=0}^{\infty} P(c|n)P(n)$$

$$= \sum_{n=0}^{\infty} \frac{\lambda^n}{n!} e^{-\lambda} \left[1-(1-2d)^n\right] \tag{4}$$

Applying the general relationship:

$$e^{a\lambda} = \sum_{n=0} \frac{a^n \lambda^n}{n!} \tag{5}$$

equation (4) becomes simply:

$$P_c = 1 - e^{-2\lambda d} \tag{6}$$

The next step is to compute λ based upon the expected vehicle density and the transmission characteristics. Assume any transmission from a source within a radius R of a receiver-relay can reach the receiver-relay and any source farther than R cannot. Two types of transmission patterns are considered, a circular pattern which covers all streets within radius R and a linear pattern which covers only the streets that intersect at the receiver-relay location. The latter is characteristic of urban high rise areas where the buildings provide a tunnel effect of restricting the signal to the streets on which the source is located. The former relates to low rise areas where the signal may propagate in all directions from the source. These patterns, of course, represent gross but necessary simplifications of the actual propagation envelope which varies according to the particular environment in the vicinity of the receiver-relay.

The number of vehicles per street mile is equal to the vehicle density, δ, in vehicles per square mile, divided by the number of street miles per square mile, M. For the linear pattern the number of vehicles in a given direction from a receiver with range R, in miles, is R times the number of vehicles per street mile. Since the receiver is at an intersection, there are four directions to be considered. Thus, the average number of vehicles inthe transmission region is:

$$\lambda = \frac{4R\delta}{M} \tag{7}$$

where

R = transmission range (miles)

δ = vehicle density (vehicle/sq. mi.)

M = number of street miles per square mile

The value for the circular pattern is derived by calculating the street length within the circle of radius R as depicted in Figure VII-2. The length of the streets that intersect at the receiver is 4R as in the linear case. The computation for the streets parallel to the North-South intersecting street is identical to that of those parallel to the East-West intersecting street. Similarly, each quadrant of the circle is identical. The length, L, within the quadrant, of the street next to the North-South intersecting street, is:

$$L = (R^2 - S^2)^{\frac{1}{2}}$$

where

S = length of block

Similarly, the length of the next street is:

$$L = \left[R^2 - (2S)^2\right]^{\frac{1}{2}}$$

There are K streets parallel to an intersecting street and within a quadrant where K is the greatest integer in R/S.

Combining the length for streets in all four quadrants and in both directions yields:

$$\lambda = \left[4R + 8 \sum_{k=1}^{K} (R^2 - S^2 k^2)^{\frac{1}{2}}\right] \delta / M \qquad (8)$$

where

$K = R/S$

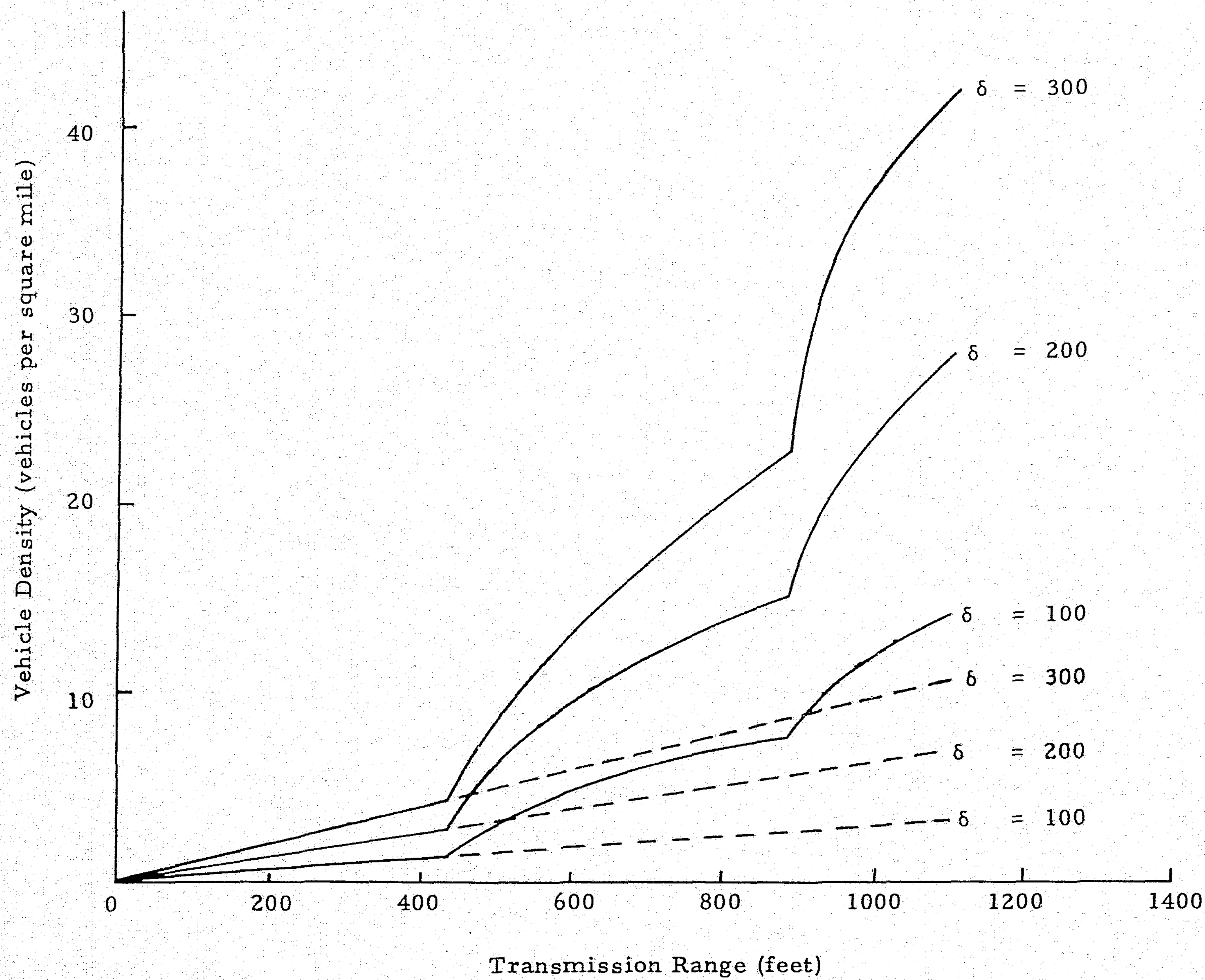
A block length, S, is defined as 440 feet (12 blocks per mile) and street length per mile, M, is 24 miles. The values of λ as defined by Equations (7) and (8) are plotted in Figure VII-3. The vehicle densities of 100, 200, and 300 vehicles per square miles are assumed to represent a typical range of values for a congested urban area such as the downtown section of a large city. Note that 10,000 vehicles assumed for Chicago in the previous chapter results in about 50 vehicles per square mile. Of course, this average throughout the city will yield much higher local densities in certain sections of the city.

Assume a transmission from a vehicle contains the vehicle code, status code and a parity bit. Assume fifteen bits for the vehicle codes, which allows over 32,000 vehicles in the system and nine bits for the status code (512 possibilities). Further assume the 500 bits/second data rate characteristic of the current citizen alarm system design, which implies a transmission time of .05 seconds. Assuming a vehicle speed of 30 miles per hour, or 44 feet per second, and two transmissions between adjacent receivers, which are one block (440 feet) apart, results in a 5-second duration between transmissions. This gives a duty cycle of 0.01.

There are, of course, an infinite number of combinations of data rate, word length, and frequency transmission that result in this value of the duty cycle.

Assuming vehicle speeds ranging from 15 to 30 miles per hour, and two transmissions between adjacent receivers one block apart (440 feet) yields a

Figure VII-3. NUMBER OF VEHICLES WITHIN TRANSMISSION RANGE



duration between transmissions ranging from 10 to 5 seconds. This gives a range in the duty cycle from 0.005 to 0.01. The contention probabilities for these duty cycles are plotted in Figures VII-4 and VII-5.

These curves represent the probability that a given vehicle's transmission is interfered with under the specific conditions and assumptions. If a standard requirement is set, such as no worse than 2% probability of contention,* one can establish that for a duty cycle of 0.01 the transmission range must be less than 200 feet, even with a local vehicle density as low as 200 vehicles per square mile. In the linear region of the curves, i.e., below 440 feet, the relationship between contention probability and duty cycle is also linear. Therefore, decreasing the duty cycle to 0.005 results in increasing the allowable transmission range to about 300 feet for a vehicle density of 200 and a contention probability requirement of 2%.

It should also be pointed out that 300 vehicles per square mile is only about two per block. This density may often be exceeded at busy intersections, taxi stands, bus terminals, etc.

The designed transmission range for the citizen alarm system is 500 feet with a 50% probability of detection. Clearly, a vehicle system with this same range would result in significant contention problems, even for relatively low vehicle densities. However, if the vehicle-borne transmitter power is decreased to a range about equal to a street width, the signal could be detected only as the vehicle passes near the receiver-relay. Further, if the receiver-relays are placed in the middle of each block, the intersection traffic problem is diminished. However, with a decreased range the duty cycle must be increased to assure transmission during the period the vehicle is within range of the receiver-relay.

*The design goal for communications coverage for the Department of Transportation's Automatic Vehicle Monitoring System is 98% successful completion of all messages from the vehicles to the communications center and from the center to the vehicles.[17]

Figure VII-4. CONTENTION PROBABILITY, d = 0.01

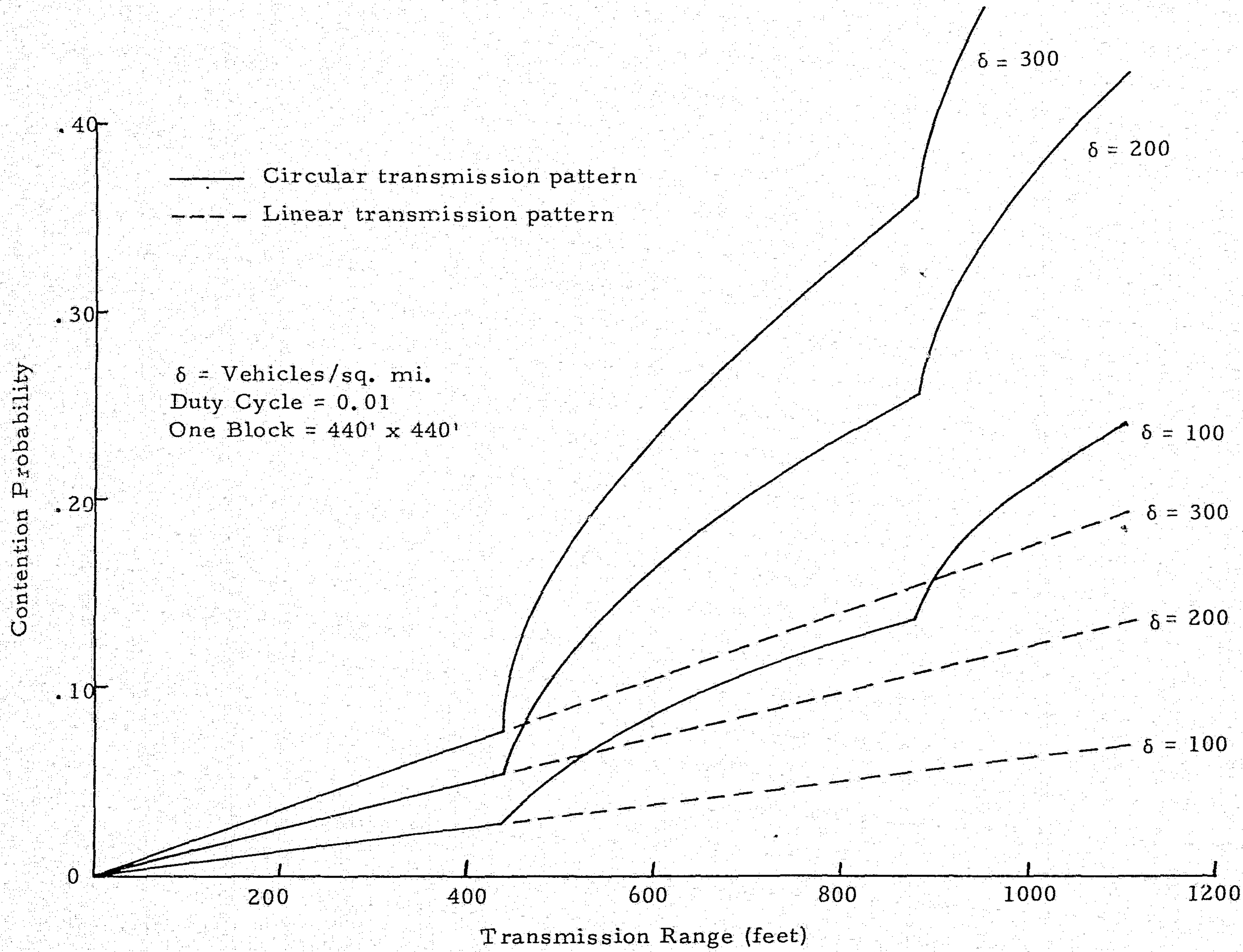
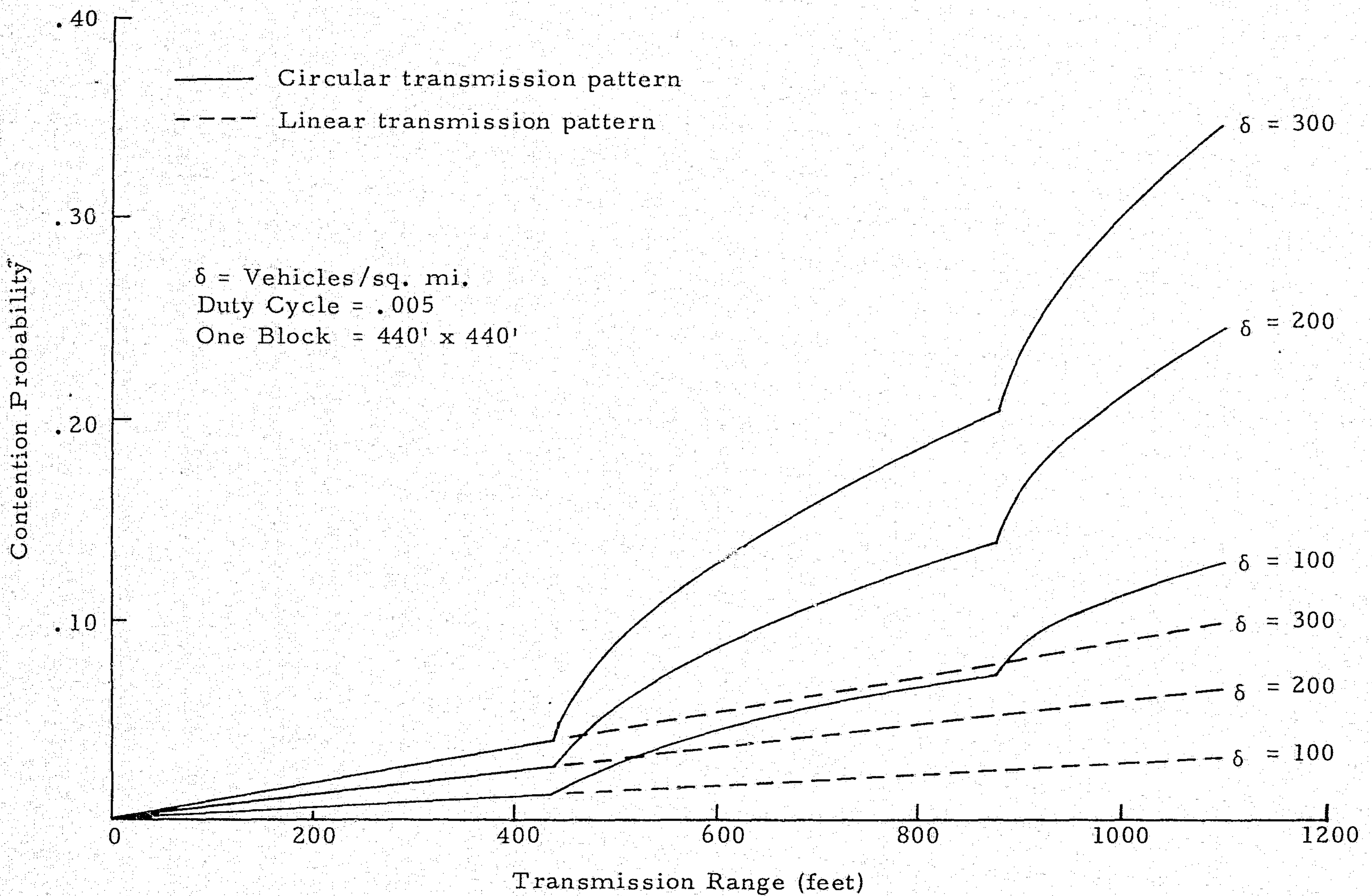


Figure VII-5. CONTENTION PROBABILITY, d = .005



For example, assume a street width of 50 feet and a transmission range of 60 feet with the receiver-relay placed along the side of the street in the middle of the block. A vehicle travelling at 30 mph in the lane furthest from the receiver-relay would be within transmission range for about 1.5 seconds. Therefore, the duty cycle should be at least one transmission every 1.5 seconds. For a transmission time of 0.05 seconds, the duty cycle is 0.033. At a vehicle density of 300 per square mile yields an average value of λ equal to .25 vehicles within transmission range. The probability of contention is then about 1.5%. For a vehicle density of 100 per square mile it is 0.5%, which implies that one out of every 200 location signals for a given vehicle would be invalid. Doubling the maximum allowable vehicle speed implies that the time between transmission must be halved thereby doubling the duty cycle. This results in approximately doubling the contention probability.

In general, it is evident that contention can present a significant problem for vehicle usage of an inverse proximity system in an urban environment.

B. DATA RATE SATURATION

The utilization of the citizen alarm system by vehicles would result in a significant increase in the data rate experienced by the receiver-relays. The rate depends upon the vehicle density, the number of transmissions per second per vehicle, and the number of bits per transmission. The data rate, R_D, is given by:

$$R_D = \lambda B T_s \qquad (9)$$

where:

λ = number of vehicles within range of a receiver-relay

B = number of bits per transmission

T_s = number of transmissions per vehicle per second

The variable λ is computed from Equation (7) or (8), depending upon the transmission pattern in the vicinity of the receiver-relay.

Figure VII-6 presents a plot of the relationship between the data rate and the vehicle density for the linear and circular transmission pattern. The data rate at each secondary receiver-relay can be determined by using a scale factor of ten since there are assumed to be ten primary receiver-relays for each secondary. Figure VII-7 presents curves for values of R and δ where the number of vehicles per receiver-relay equals six, or equivalently, the data rate from the secondary receiver-relay equals 300 bits/second. This rate is the maximum that can be accommodated by the citizen alarm system design previously costed.

As noted in Chapter III, the present citizen alarm system design entails a data storage capacity per primary receiver-relay of 256 bits or about 10 vehicle codes of 25 bits each. At a data rate of 300 bits per second, this implies 0.85 seconds to transmit a receiver-relay's data. Assuming ten primary receiver-relays for each secondary, each primary would be sampled

Figure VII-6. DATA RATE vs. VEHICLE/RECEIVER RATIO

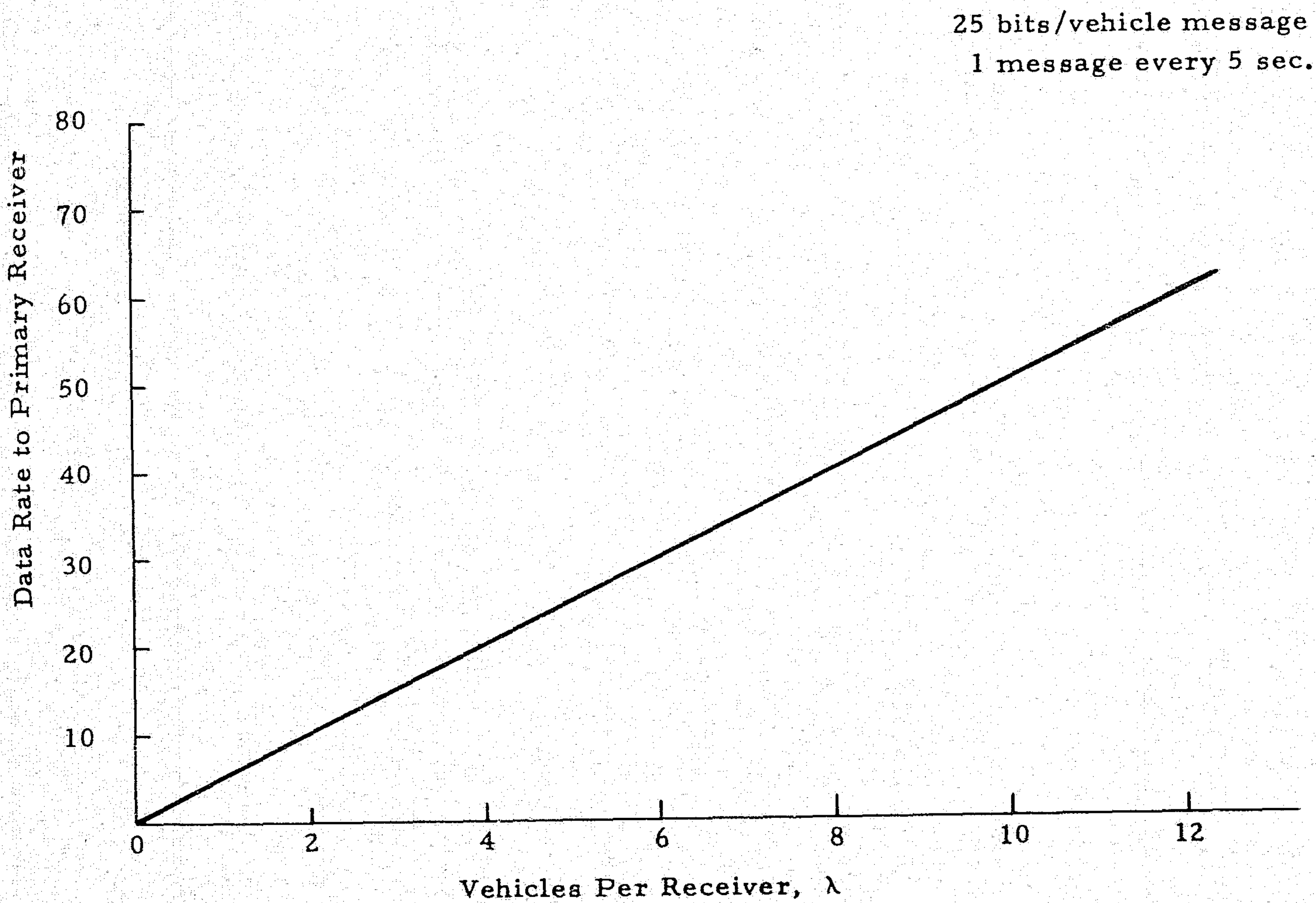
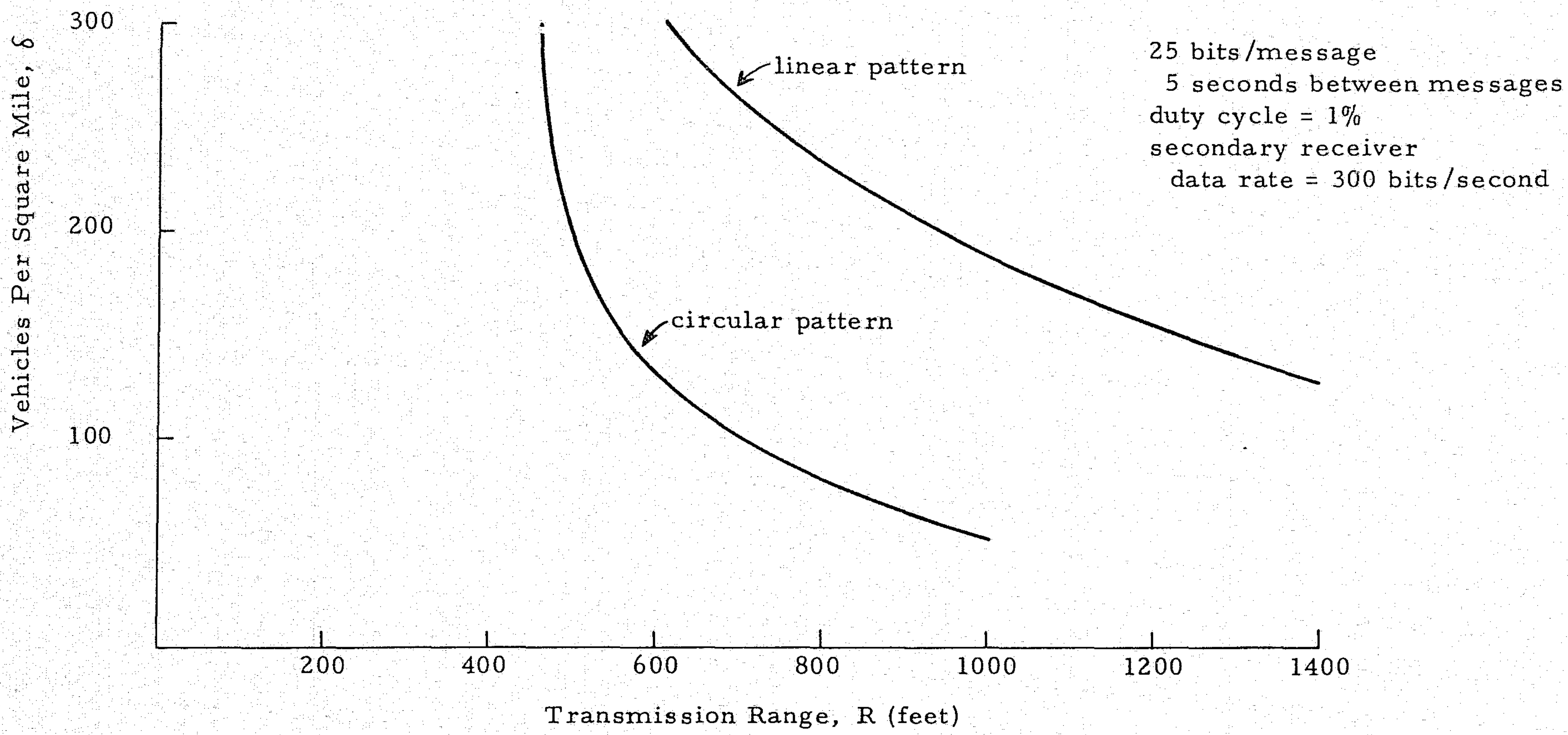


Figure VII-7. CONSTANT DATA RATE CURVES



every 8.5 seconds at a maximum. This implies 10 vehicle codes every 8.5 seconds or 1.18 vehicles per second per receiver-relay. If each vehicle transmits once each 5 seconds, a maximum of 6 vehicles can be accommodated per receiver-relay as indicated in Figure VII-6 for a 30-bit-per-second data rate per primary receiver-relay. The sampling rate of one per 8.5 seconds compares favorably with the once-per-9-second rate assumed for the RF direct proximity system for vehicle location.[5]

If we select various R, δ values from the circular pattern curves of Figure VII-7, and determine the resulting value of contention probability from Figure VII-4, we note that these probabilities are quite significant. For example, the point R = 500 and δ = 200 which lies on the curve representing data rate = 300, results in a contention probability of about 11%, which is quite high. The point (700, 100) results in a similar value as does (460, 300). Similar results are obtained using the linear pattern curves. This implies that the contention problem is much more significant than the data rate saturation problem. Of course, if the number of primary receiver-relays per secondary receiver-relay were increased, the data rate from each secondary would increase proportionately, resulting in saturation for a lower level of vehicle density.

In addition, the system can easily be redesigned to increase the data rate capability -- at additional cost, of course -- while the technical problem of alleviating contention has not yet been resolved.

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