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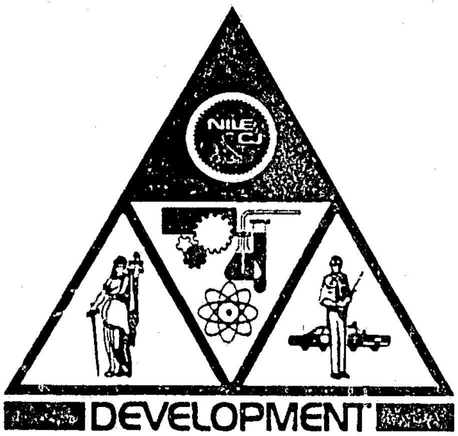
EQUIPMENT SYSTEMS IMPROVEMENT PROGRAM

SURVEY AND TECHNICAL ASSESSMENT CARGO SECURITY SYSTEM

Law Enforcement Development Group

July 1974



Prepared for

NATIONAL INSTITUTE OF LAW ENFORCEMENT AND CRIMINAL JUSTICE
Law Enforcement Assistance Administration
U.S. Department of Justice

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EQUIPMENT SYSTEMS IMPROVEMENT PROGRAM

SURVEY AND TECHNICAL ASSESSMENT
CARGO SECURITY SYSTEM

Approved

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ABSTRACT

Theft of truck cargo in transit is causing a multi-billion dollar loss to the trucking industry. An examination of the theft problem is made to determine the make-up of the industry losses, the theft prevention systems in existence, and the most cost-effective means to counter theft and reduce the losses.

It is found that there are no existing theft prevention systems which meet all performance requirements identified by the trucking industry. While direct surveillance of vehicles by security forces provides the most effective tool, it is expensive and consequently is currently limited to vehicles carrying high value cargo.

A two-step cargo protection program for reducing losses from cargo theft is proposed: a cargo security program with its major goal a reduction in thefts from cargo trucks, and a companion cargo accountability program aimed at developing systems for the tagging of cargo to provide traceability of shipments. Technical concepts for a cargo security system are developed and a development plan defined. (Description of the cargo accountability program is limited to basic concepts and to the way it interfaces with the cargo security system.)

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FIGURES

TABLE

ACKNOWLEDGMENTS

The information contained in this report represents the combined efforts of staff members of The Aerospace Corporation working in conjunction with representatives of the trucking industry. In assessing the magnitude of the cargo loss problem, identifying the theft prevention measures employed by the industry, and reviewing proposed technical concepts, valuable contributions have been made by the officers and members of the Association of Transportation Security Offices (ATSO), the California State Trucking Association, the New York State Trucking Association, the Los Angeles Police Department, and the Los Angeles County Sheriff's Department. The assistance of Mr. Lee R. Sollenbarger, Chairman of the Board, and Mr. Harlan Flinner, Director of Loss Prevention, both of Transcon Lines, in providing the industry viewpoint and in making available facilities during the concept development phase, is particularly appreciated.

The principal author of this report, Mr. G. D. Wilson, was assisted during the concept development of the cargo security system by various members of The Aerospace Corporation staff, in particular Messrs. P. Broderick, D. Flagg, M. Jensen, H. King, L. Martinez, and E. Skomal.

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Finally, acknowledgement is due to Mr. H. W. Nordyke for his guidance and direction of the program.

SUMMARY

Cargo theft has become a highly organized multi-billion dollar business, with a network of intelligence agents, drivers and freight handlers, and an efficient distribution system for the stolen goods. Although the direct dollar loss of stolen goods in the trucking industry is substantial (more than $1.6 billion dollars in 1972), there are greater "indirect" losses that must be considered to evaluate the real loss to the national economy. The motor carrier, whose high insurance deductible makes him virtually self-insured, incurs an indirect cost of processing loss claims by the shipper of between $2 and $5 for each $1 of direct loss. The shipper's indirect costs (lost or delayed sales, higher freight rates, etc.) are estimated at between $5 and $7 for each $1 of stolen cargo. As a result the consumer pays increased prices for goods and the government loses duty and tax revenues at federal and state levels. It has been estimated by a Senate Select Committee[1] that the real cost of this criminal activity to the national economy could thus well approach an annual loss of $10 billion.

This survey and technical assessment report describes the cargo theft problem in the trucking industry and proposes a two-step integrated approach to stem the increasing cost to the nation caused by this criminal activity. The first step, a Cargo Security Program, is aimed at the reduction of thefts that occur at the vehicle interface. The second step, a Cargo Accountability Program, will build upon the first and is intended to develop theft prevention measures within transhipment areas to provide traceability of stolen goods.

Cargo Security Program

More than 60 percent of the losses in the trucking industry involves the use of the cargo vehicle, either as a direct target (hijackings) or as a means for the distribution of stolen goods. Hijackings of entire vehicles, which are much more profitable to the criminal than bank robberies, represent only ten percent of the total theft loss in the trucking industry. The remaining losses, which are the result of organized theft of one or more cartons of valuable goods, represent to the carrier a significant percentage of after-tax profits, in some cases as much as 50 percent. The Cargo Security Program is aimed at developing a security system to provide a major reduction in these vehicle-related thefts (not only the highly publicized hijackings but also those which involve collusion of drivers and freight handlers in the theft and fencing of partial loads).

An overriding factor in the development of such a cargo security system is its value to the individual trucking fleet operator. A Senate Select Committee[1] and the Department of Transportation[3] have shown a direct relationship between theft losses and gross revenue, and a value analysis indicates that the life cycle cost of a theft prevention system should not exceed $1000 per vehicle year.

Development of the requirements for a cargo security system was based on a survey of current hardware available to the trucking industry and current procedures and techniques employed by security officers in the industry. In determining the functional requirements of the system, emphasis was placed on the effectiveness of these theft prevention measures irrespective of the cost of implementation. Direct surveillance of the vehicle by security forces was found to provide the most effective tool in detection and prevention of cargo theft; however, because of its expense it is currently limited to vehicles carrying high value cargoes and to drivers under suspicion of being involved in cargo thefts or distribution of stolen goods.

The concept of the cargo security system is to provide for low-cost surveillance of each cargo vehicle by security management. Sensors and logic on the vehicle and in the dispatcher's office would provide data describing suspicious activities at the vehicle such as:

- Unusual activity in the driver's compartment (opening of doors, changing of seat positions), usually symptomatic of a hijack condition
- Entry into the cargo compartment at other than authorized locations
- Deviation of the vehicle from an anticipated sequence of authorized stops, or an anomalous vehicle location

In addition, a means for ascertaining the location of the vehicle is required to enable security officers or law enforcement agencies to intercept it if necessary.

Components and subsystems to perform these functions are within the state of the art. The vehicle location subsystem, a principal cargo security system element, is probably the highest single cost item and its selection is critical to the program. While many vehicle location technologies have been propounded, few have been tested operationally and none can meet the system cost objectives.

Concept development work conducted by The Aerospace Corporation during FY 74 has identified two candidate location technologies which can meet the cost performance goals for the system. Each technology is a hybrid of navigation techniques to compensate for the errors inherent in low-cost stand-alone systems.

Further studies and analyses, supported by operational testing of engineering prototype units, will establish requirements for an operational cargo security system.

Cargo Accountability Program

A Senate report[1] has found that there has been little effort to provide for adequate documentation, package marking, and identification of responsibility for cargo shipments from point of origin to point of destination, with the result that the point at which theft loss occurs--in the transport chain of labeling, packaging, loading, transit, storage, unloading, and delivery--cannot be determined. Lack of merchandise or crate/carton identification codes, easy access to shipping documents, and inadequate verification methods for items shipped constitute an open invitation to the cargo thief.

Cargo loss statistics are categorized into three general areas: theft, damage and shortage. Because of the inadequate cargo accountability methods throughout the trucking industry, proof of theft is difficult to establish, with the consequence that many losses categorized as "shortages and shrinkage" in the compilation of loss statistics are in actuality the result of theft.

The Cargo Accountability Program is aimed at developing a system to reduce these theft losses. Conceptually, an audit trail of the movement of each unit of cargo through the distribution chain can be accomplished by the use of cargo "tags" and monitor units at each mode interface. Because the cargo vehicle is the most frequently used interface, a means must be found to monitor cargo movements into and out of the vehicle, and to report these movements to the audit mechanism. (The cargo security system described in this report provides such a reporting capability and will be designed to accommodate a cargo accountability sensor.)

The costs of a cargo accountability system must be such that its deployment can be economically justified by the industry. To provide this justification, the savings accruing from reduction of shortage and shrinkage losses, combined with those resulting from the improvements in accounting efficiencies to be gained by the introduction of a "paperless" audit trail, must more than offset initial installation and annual operating costs.

Standardization of tag codes is the key to the implementation of the system in that cargo units pass through many interfaces under the control of different organizations in their movement from origin to destination and, consequently, a unique code capable of being "read" by monitors at each interface is essential.

In summary, the Cargo Accountability Program is a logical extension of the Cargo Security Program described in this report and can further reduce trucking industry theft losses.

CHAPTER I. INTRODUCTION

Cargo theft is a serious national problem causing an annual multi-billion dollar loss to the nation's economy. The ever-increasing loss rate and growing evidence of highly organized theft rings has brought attention to the problem at the highest government levels. In FY 1974, under a Law Enforcement Assistance Administration (LEAA)-sponsored task, The Aerospace Corporation initiated a study of a Cargo Protection Program intended to reduce the opportunities for cargo theft. The overall program consists of two elements: a Cargo Security Program aimed at developing a low cost, reliable security system to alert security officers of unauthorized access to cargo-carrying road vehicles, and a Cargo Accountability Program, intended to develop an accountability system for "tagging" cargo in transit from point of manufacture to ultimate user to provide shipment traceability. Because the road vehicle is the principal element in the distribution process, the development of the security system is a prerequisite to the development of the accountability system.

The purpose of this report is to describe a survey and assessment of the requirements for the cargo security system and to discuss the development of system elements. Discussion of the cargo accountability system is limited to basic concepts and to the way it interfaces with the security system since the Cargo Accountability Program is not presently funded.

In performing the cargo security system study, Aerospace investigated the characteristics of the cargo loss problem and reviewed theft prevention concepts with officers of the national and state trucking associations and with the national trucking security offices association. It was found that more than one-half of the total theft losses are vehicle related and that the most effective (but most expensive) preventive measure was the use of armed escorts or roving security officers to spot check vehicles and loads. These findings and the considerations of available hardware and development capabilities led to the determination that a low cost security system which would provide protection equivalent to direct surveillance by security personnel was both feasible and desirable.

The conceptual cargo security system is depicted in Figure 1. Sensors monitor the integrity of the cargo and driver's compartments and the movement and location of the vehicle. Transmission of status and location data is made via a communications channel to the fleet dispatch office unit which provides a display of anomalous or alarm conditions and the location of the monitored vehicle. Full details of the system are presented in Chapter V.

The material in this report is organized by chapter in the following manner:

Chapter II	Presents the major study conclusions
Chapter III	Reviews cargo loss data, identifies vehicle-related theft losses, and determines the economic value of a cargo security system to the individual trucking fleet operator

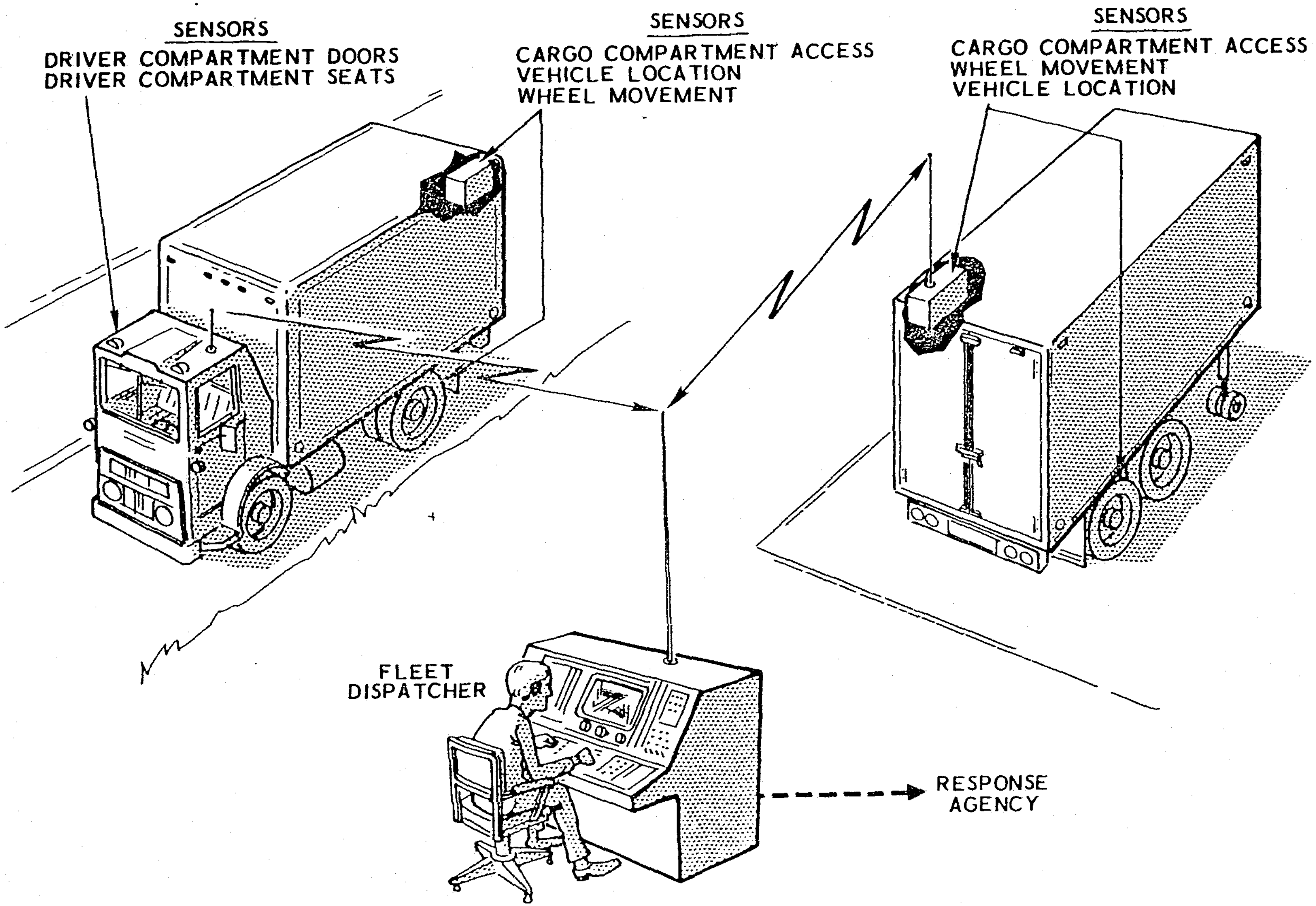


Figure 1. Cargo Security System Concept

Chapter IV	Reports on current security procedures and systems and their effectiveness
Chapter V	Identifies the theft prevention techniques required and determines technical requirements
Chapter VI	Reports on state-of-the-art vehicle location systems, identifies deficiencies, and selects promising technological solutions
Chapter VII	Presents development concepts in terms of specific hardware and studies

These chapters are supplemented by appendices containing detailed information on a low-profile communication antenna, data channel requirements, proximity systems, battery units, dead reckoning location, use of broadcast stations for vehicle location, and interception requirements.

CHAPTER II. MAJOR TECHNICAL CONCLUSIONS

A study has been made of the cargo loss problem in the trucking industry and a program for theft prevention has been established.

The following conclusions can be drawn from this study:

- Cargo theft in the trucking industry is a very serious and costly problem in need of immediate attention. Over 60 percent of current losses involve the use of the cargo vehicle in the theft and distribution of goods. This use is growing as more conventional alarms are being installed at freight depots.
- Cargo protection systems against vehicle-related theft in the trucking industry have not kept pace with the advancements of technology. The few systems offered are limited in capability and no barrier to the sophisticated thief. Surveillance by security officers is the only currently effective prevention measure and any cargo security system should provide similar real-time surveillance of vehicle location and operating status.
- To be of value to the trucking industry, the cost of a cargo security system must be commensurate with the ratio of losses to revenues. The study shows that the system life cycle cost should not exceed $1000/vehicle/year.
- The technology for the design of a cost-effective cargo protection system does exist, and it can be applied to the solution of the vehicle associated theft problem. Vehicle status sensors offer

the greatest potential for effective cargo protection. The electronics industry has developed the components for most of the sensors needed with the exception of those for the vehicle location sensor. Since the location sensor is not only a critical security system element, but also the most costly, its successful development is the chief problem to be faced. Two hybrid location systems with the potential to meet performance requirements at low cost have been identified.

- A cargo security system concept has been identified which provides for the real-time surveillance of the integrity and location of each cargo vehicle in a trucking fleet, automatic reporting of abnormal situations, and rapid interception of the vehicle by a response agency. This system is intended for use by carriers of valuable merchandise in single load or mixed load operations within urban areas. Inherent in the concept are the primary considerations of low cost, low false alarm rates, and independence from driver action.
- A coordinated cargo security system development and study effort, supported by operational testing of prototype units, is planned. This effort should result in state-of-the-art hardware designs that can reduce the cargo theft problem within a reasonable period of time. The design objective of providing cost-effective cargo security hardware to the trucking industry necessitates government funding of costly development items.

- The Cargo Accountability Program (not presently funded) is a logical extension of the Cargo Security Program. Therefore, the design of the cargo security system conceptualized in this report is intended to provide for the addition of cargo accountability hardware and thus complete the integrated cargo protection system.

CHAPTER III. THE NEED FOR A CARGO SECURITY SYSTEM

A. Cargo Losses in the Trucking Industry

1. Direct losses. Losses in the trucking industry from the theft of cargo in transit represent more than 60 percent of the national multi-billion dollar total that is lost in all transportation modes. Statistics[1] on trucking industry theft losses show that the direct loss value, or released liability value, of the stolen cargo was $900 million in 1970. These theft losses are rising at a rate significantly beyond that projected in 1970, as shown in Figure 2 which illustrates the loss trend through 1972. Data on 1973 losses were not available as of the writing of this report, but the value is expected to reach $1.8 billion.

2. Indirect losses. The direct losses due to cargo theft represent but a small proportion of the total loss to the national economy. The balance of the loss is the result of two major indirect cost items, those of the carrier and those of the shipper.

   a. Carrier indirect loss.

   - Claim processing. Each unit of cargo which fails to reach its intended destination by reason of theft is the subject of processing action by the carrier in response to the shipper's loss claim. (Since the typical cargo insurance policy includes a large deductible and a maximum payment limit, the carrier is effectively self-insured.) Estimates[1,2]

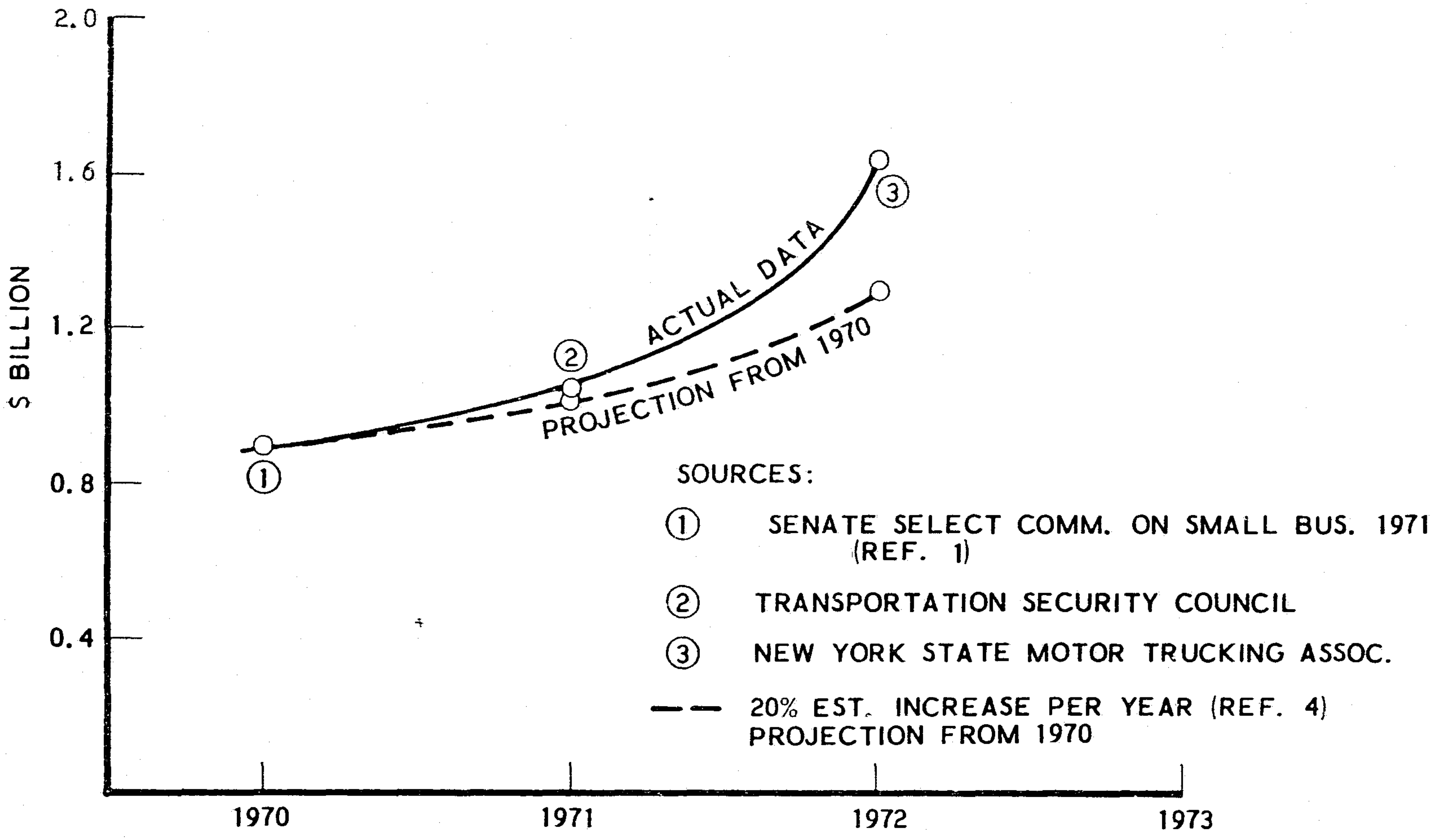


Figure 2. Direct Cargo Value Crime Loss Trend for Trucking Industry

indicate that in the administration of these claims both the claimant and the party against which the claim is filed incur costs between two and five times the amount of settlement.

b. Shipper indirect loss. The indirect cost of cargo thefts to the shipper is composed of many factors, the more significant of which are as follows:

- Delayed sales. The practice of selling goods f.o.b. at the manufacturers' shipping points is changing as a result of the high incidence of loss in transit. The consignee is taking the position that payment will be made only after delivery of the cargo, with the result that the manufacturers' cash flow situation is changed.
- Lost sales. Many goods are seasonable and their theft in transit results in major losses. Advertised sales items may not be available with the resultant loss of customer goodwill.
- Embargoes. Rather than face potential theft, many motor carriers are refusing to haul theft-prone goods. This embargo restricts the free flow of commerce. The small business man, unable to exert the economic leverage available to his larger competitors in breaking such embargoes, is the principal loser.

- Increases in prices and freight rates. Rather than pay the high cost of claim processing, many victims of the cargo thief cover their losses by increases in freight rates, which in turn are passed on to the consumer.
- Unfair competition. Stolen goods reenter the legitimate distribution channels at many levels, thus constituting unfair and illegal competition.

It has been estimated[1,2] that the indirect cost to the shipper resulting from these factors is between five and seven times the direct loss.

It should be further noted that the inability to collect duty and tax revenues on stolen cargo, reduced income tax receipts from uninsured theft victims, and loss of foreign currency for stolen export cargo adds to the total loss to the national economy. It has been stated that this total loss could well approach $10 billion annually.[1,2]

3. Loss ratios. Carrier losses are composed of damage, theft, and "missing items," this latter category often being employed to cover known but unproven thefts. The breakdown of these categories will vary from carrier to carrier depending on the level of security employed by the carrier and the nature of the goods carried. The overall carrier average shows that the ratio of losses to revenues due to cargo theft alone represents some 1.4 percent of total revenues.[3]

B. Categorization of Cargo Theft Losses

Cargo theft losses by the carrier can be categorized into four groups:

- After-hours break-in. Theft of cargo from freight depots or storage areas during non-working hours
- Hijacking or grand larceny. Theft of entire loads:
    - Armed hijack of a road vehicle
    - Theft of an unguarded road vehicle
    - Theft of a parked cargo trailer
- Theft of partial loads. Theft of one or more cartons or containers:
    - Armed theft from a road vehicle
    - Theft from an unguarded road vehicle
    - Theft from a parked cargo trailer
    - Theft from freight depots or storage areas during working hours
    - Deliberate short delivery of cargo
- Pilferage. Theft of the contents of a single carton or container

C. Distribution of Cargo Losses

The Interagency Committee on Transportation Security, a 14-member interagency body chaired by the Department of Transportation, has performed analyses of the cargo theft problem[3] and found the following distribution pattern:

- 5% - After-hours break-and-enter burglaries
- 10% - Armed hijacks or grand larcenies of entire trailers or containers
- 85% - Individual thefts during the course of normal operating procedures and regular operating hours of the transportation system by persons having authorized access to cargo and cargo-handling areas by transportation mangement, including shippers and receivers, with the stolen goods being carried out the front gates of transportation terminals on vehicles or by persons authorized to be in the terminal area. Of this 85 percent, 60 percent is more than one case, but less than a full load, with 25 percent being less than one case.

D. Vehicle-Related Crime Losses

A breakdown of truck cargo crime losses according to the methods and circumstance of crimes is shown in Figure 3. It is seen that the vehicle-related thefts comprise a major share of the total:

- 2.5% - After hours break-ins of parked vehicles
- 10% - Hijack or grand larceny
- 40 to 60% - Partial load thefts. These thefts occur both at the freight depot and during pickup and delivery operations, and the distribution is proportional to freight depot security.

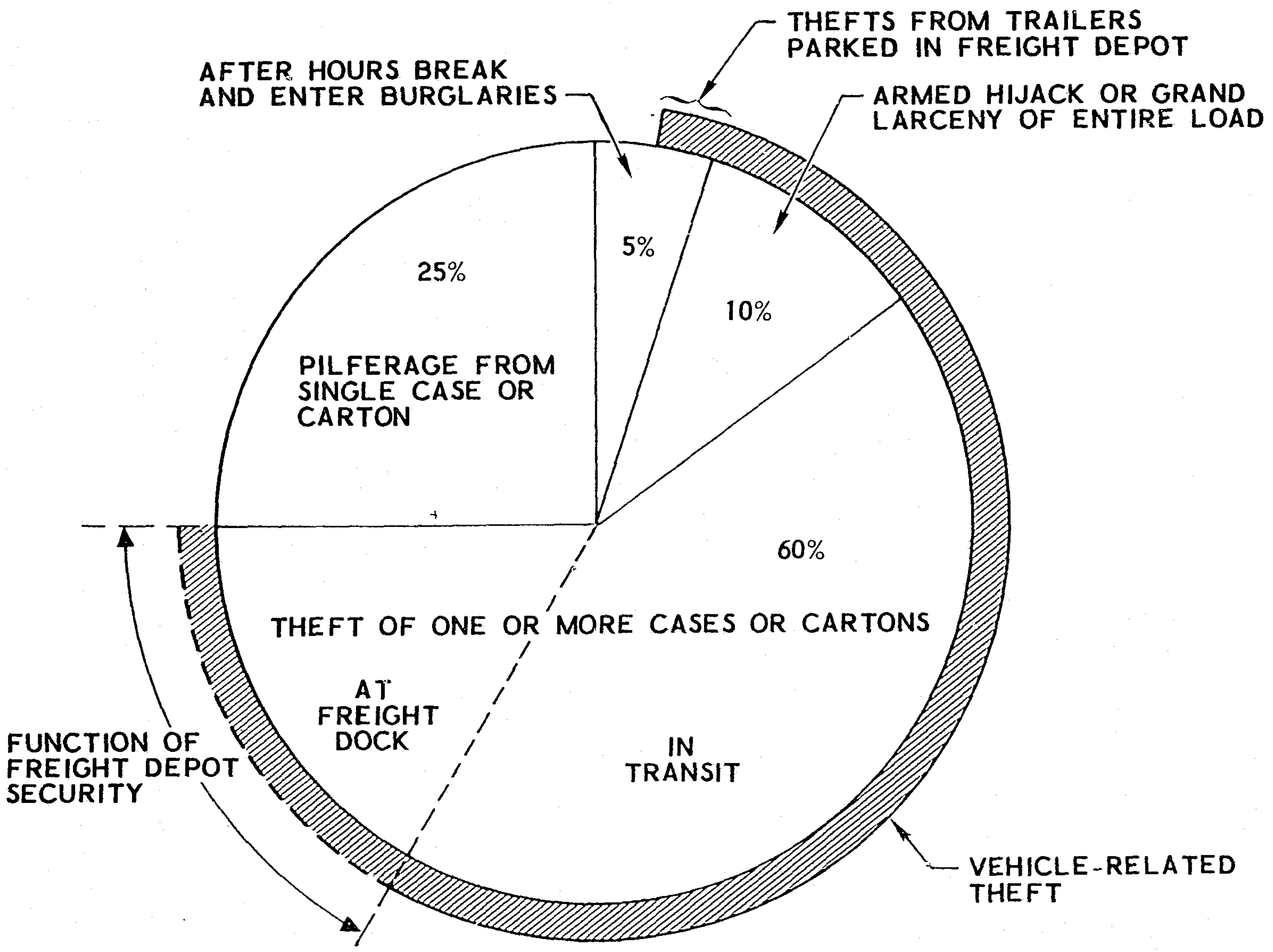


Figure 3. Truck Cargo Loss Breakdown

Consequently, any security improvements at the depot will tend to shift the crime emphasis to road operations, making tighter vehicle security measures mandatory.

There is mounting evidence[1,2,4] that organized theft and hijack operations are occurring on a demand basis for certain goods with well established channels for disposition of goods. It is estimated[4] that more than 60 percent of cargo thefts involve collusion of the truck driver and up to 80 percent involve collusion with some employee or guard. There is often collusion between drivers of different trucking companies and freight handlers at various interfaces. The disposition of stolen goods is highly organized (Figure 4), and an examination of the theft ring operation indicates that, because of the multiplicity of fences and buyers, the logical point of attack against the ring is at the vehicle interface. This logic has been confirmed by the security officers of trucking organizations who have found by experience that surveillance of the vehicle and of driver actions provides the most effective countermeasure to cargo theft. Spot checking of a loaded vehicle against the cargo manifest is an effective means (albeit time consuming, cumbersome, and expensive) of detecting vehicle-related cargo theft activities. Often such checks reveal the presence of unauthorized goods in the cargo compartment, suggesting that regular delivery operations form an integral part of an illegal distribution system.

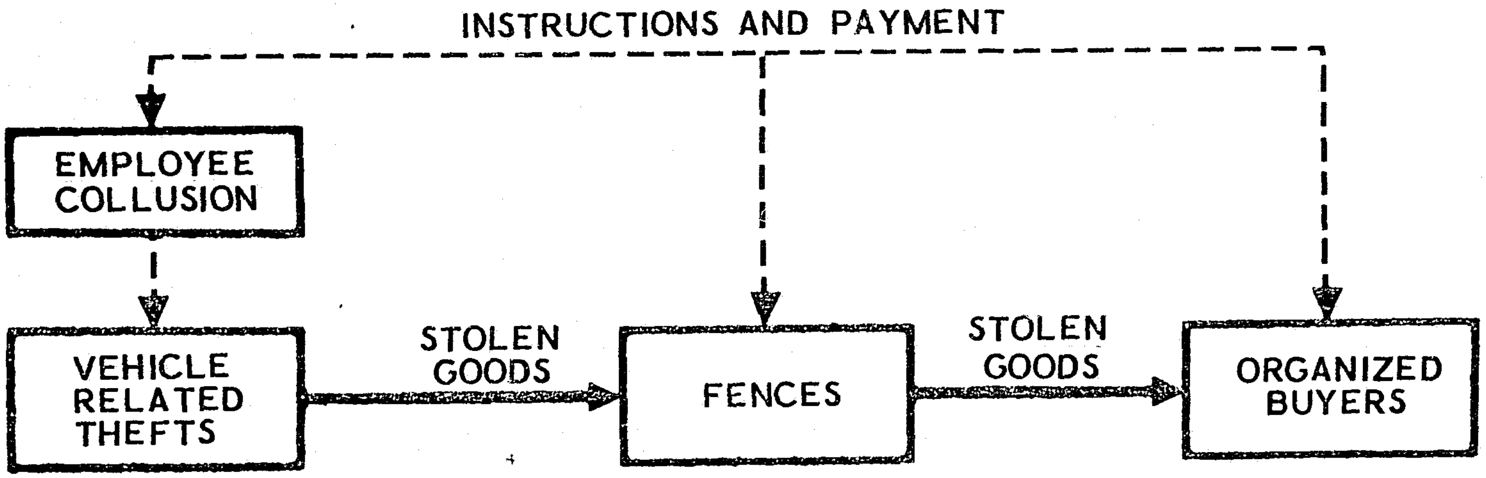


Figure 4. Theft Ring

E. Functional Requirements for Theft Prevention

A review of the vehicle-related cargo theft situation with the national and state trucking associations, national transportation security officers association, and law enforcement agencies has been conducted and a set of functional requirements has been established to serve as a basis for the development of an effective theft prevention system. While it is recognized that positive cargo identification (which would be provided by the integration of the Cargo Accountability Program) must ultimately be employed to counteract all facets of cargo theft including those categorized as "shortages," it is the consensus that a system having the characteristics described in this report can be a highly effective theft prevention measure against the majority of vehicle-related thefts.

1. Deterrence. Presenting the would-be thief with the knowledge that he and his vehicle are under constant surveillance is a powerful deterrent to criminal activity. This has become evident from the marked decreases in theft when drivers become aware that a security officer is spot checking cargo and for a short period following the installation of a new "black box," however ineffective, on the vehicle.

2. Detection. Detection of a direct attack on the vehicle or suspicious circumstances surrounding the actions of the driver and his vehicle must be reported to the dispatcher immediately. Means must be provided to sense radical departure from normal routes, entry into the cargo compartment at unauthorized stops, and unusual activity in the driver compartment.

3. Interception. When a warning or alert condition is detected, the dispatcher must have the means available at his immediate disposal to alert law enforcement agencies (or private security guards) of the vehicle location. Disablement of the vehicle by the system can provide an improved probability of interception, but for driver protection purposes, this function should be exercised only under strict security management control.

4. Human interfaces. Although there are many honest drivers, the vehicle system must operate under the premise that the driver will attempt to defeat the system, and, consequently, its design must provide for appropriate protection.

The dispatcher function must be automated to the extent that the system will report warning or alarm conditions, identify the vehicle, and specify its location without need for manual intervention.

5. Data privacy. Although there is recognition of the need for concerted action by industry to combat cargo theft, the system should not compromise data which is considered proprietary. The motor carrier industry is highly competitive, working on a low profit margin, and each company regards data pertaining to its routes, customers, and dispatch priorities as critical to profitable operations. Consequently, the concept of a central system which contains such data, however well protected, is generally unacceptable to the industry at this time.

F. System Value Analysis

The value of a cargo security system to the management of a trucking activity is tied directly to the potential savings in vehicle-related cargo losses. The majority of these losses occur in urban pickup and delivery operations. A survey of cargo movement in this category shows that the average single-body vehicle will perform 15 deliveries and 15 pickups per day with an average load per operation of 500 pounds, or a daily total of 15,000 pounds. Urban freight rates vary with the dimensions and weight of the cargo unit delivered or picked up at each stop, but can be assumed to be between 3 and 5 cents per pound. If these cargo/cost figures are applied to a five-day week, 52-week-a-year schedule, freight revenues average between $117,000 and $195,000 per vehicle year.

A relationship[3] between gross revenues and theft loss has been established at 1.4 percent. By allocating a proportion of these losses (between 40 and 60 percent) to the vehicle, the value of the system can be determined. In Table 1, it is shown that by using a conservative (0.5 percent) ratio of direct vehicle-related theft loss to gross revenue and a rather conservative doubling figure for claim processing, the theft loss per vehicle is nearly $2000 per year. This establishes an upper bound for the system cost per vehicle year. Given the likelihood that no system can be 100-percent effective, the useful upper bound is placed at 50 percent, or approximately $1000 per vehicle per year.

Table 1. System Value Analysis--Urban Pickup and Delivery Operations

Typical Gross Revenue/Vehicle	$130,000/Year
Vehicle-Related Theft Losses at 0.5% of Gross Revenue	650/Year
Claim Processing Factor (2:1)	1,300/Year
Total Vehicle-Related Theft Loss	$1,950/Year

Although a Department of Transportation report[5] has shown that a reduction in theft-related claims can result in an increased profit of 50 cents for each $1 invested in security measures, trucking industry management has been reluctant to make such investments in security equipment alone. However, management has recognized the improved efficiency obtainable from a knowledge of vehicle position, an efficiency conservatively estimated at five percent,[6] and a system providing the dual benefits of vehicle location and theft loss reduction is attractive to the industry.

CHAPTER IV. SURVEY OF EXISTING CARGO PROTECTION TECHNIQUES

A survey of current techniques related to cargo protection has been conducted to provide a basis from which to project a Cargo Security Program. Descriptive materials have been solicited from vendors, and liaison has been maintained with various trucking security organizations to ascertain the effectivity of such techniques.

The survey shows that while there are subsystems and components which provide various levels of protection, there are no extant systems which meet all the performance requirements identified by the trucking industry as necessary to combat the ever-increasing theft problem.

Current techniques can be divided into four general areas which are employed in various combinations: procedural, theft prevention devices, theft detection and reporting systems, and vehicle tracking systems.

A. Procedural

Many trucking operations rely on the driver of the vehicle to maintain contact with the fleet dispatcher and to advise him of his location, of the status of his load, and of any direct attack on the vehicle. Two factors militate against the effectiveness of this approach, (1) the fact that more than 80 percent of cargo theft involves company employees, particularly drivers, and (2) the threat of physical violence by the thieves against the honest driver.

In an attempt to counteract the dishonest driver, many trucking organizations are concentrating on pre-employment screening. Polygraph tests are becoming a prerequisite to employment, and a data bank on driver histories is being organized. However, periodic checking of employed personnel is rarely conducted, opposition of the labor union being the principal factor.

A second theft prevention technique is the spot investigation of road vehicles by the truckers' security officers, where the vehicle load is checked against the cargo manifest.

For protection of high value loads from the hijacker, a driver of proven integrity is selected, a shotgun guard rides in the cab, and the vehicle is placed under surveillance by a trail car or a helicopter.

The cost of surveillance by additional security personnel and vehicles precludes such procedures except in those special cases where a high value cargo must be protected or a particular driver is under suspicion.

B. Theft Prevention Devices

These devices are intended to prevent access to the cargo compartment of the vehicle or to prevent the theft of the vehicle.

1. <u>Cargo compartment locks</u>. Padlocks are the principal theft prevention devices for protection of cargo compartments. Use of cylinder pulling tools or bolt cutters, stock-in-trade of all but the most amateur thief, limits protection by this means to two or three minutes.

2. <u>Kingpin locks</u>. An experienced driver can couple a tractor to a parked trailer in less than three minutes. To prevent engagement of the "fifth wheel" coupling, kingpin locks are employed. There are two typical uses for this device. The first application is to prevent the quiet, surreptitious removal of a loaded trailer parked in an area accessible to the street.

The second application is to prevent or deter the unauthorized removal of a parked trailer from an area which is not under constant surveillance. The MITRE Corporation, under the sponsorship of the Department of Transportation, performed an evaluation of eight commercially available devices in this category. Its report[7] indicated that all units were suitable for protection against rapid, surreptitious removal, but that only one, the improved Best Lock Company Model 2J7D21, could be regarded as a high security device capable of affording protection against the poorly equipped or semi-skilled thief for more than a few minutes.

3. Ignition immobilizers. Disabling of the ignition circuits of the prime mover is employed for two purposes (1) disablement of an unattended vehicle, and (2) disablement of a moving vehicle when an attack is detected. The unattended vehicle systems, marketed by Babaco Alarm Systems, Inc., and Transeco, Inc., consist of a timer mechanism which is set for a period of time by the driver or the depot supervisor. The vehicle cannot be started until the preset time has elapsed. Tests have been carried out to use this timer concept in an inverse manner, whereby the vehicle can be started and driven during the timer run-down period, but will be immobilized after the prescribed time, the concept being that the driving time of a delivery vehicle between two points can be determined from previous experience with reasonable accuracy and that this time will only be exceeded if the vehicle is hijacked. Other variations on the inverse timer concept initiate the timer run down when a vehicle door is opened while the engine is running.

A system installed for Nelson Distribution Corporation (a carrier of high-value clothing), by its subsidiary, Design Controls, provides a capability for the fleet dispatcher to remotely disable the vehicle via radio command.

C. Theft Detection and Reporting Systems

Systems are available for the detection and reporting of tampering with parked and enroute vehicles.

1. Parked vehicle systems. Babaco Alarm Systems, Inc., and the American Multi-Lert Corporation market theft detection systems to the trucking industry for the protection of parked vehicles. These systems incorporate door monitors and vehicle movement sensors to actuate the alarm mechanisms. The usual alarm system consists of an audible and/or visual alarm mounted on the vehicle. Options provide for a silent alarm capability with alarm data transmitted via a low power RF link to the security guard or via an automatic dialer to the local police or private guard service.

2. Enroute vehicle system. Design Controls, Inc., a subsidiary of the Nelson Distribution Corporation (a high value cargo carrier), has installed a remote status monitoring system on 200 Nelson vehicles. This system reports the opening of the vehicle door to the fleet dispatcher via the vehicle's two-way radio system. The Nelson operation is run on the basis of preplanned routes and schedules, and the dispatcher must determine by reference to the plan whether or not the door opening is normal or the result of a hijack. As described earlier in this chapter, the dispatcher has the capability to remotely disable the vehicle's ignition system.

D. Vehicle Tracking Systems

Tracking systems are utilized to identify and track one vehicle from a second vehicle for the purposes of (1) directing interception of a stolen vehicle by law enforcement agencies, and (2) covert surveillance.

1. Truck top markings. Markings on the tops of trucks/trailers enable an airborne vehicle to identify and track the stolen vehicle. Range of operation is governed by line-of-sight and weather conditions, and, for this reason, the airborne vehicle's probability of detection is highly dependent upon an accurate estimation of the stolen vehicle's position and on the height of buildings in its immediate vicinity. A report by the Department of Transportation[8] presents data on the ability of a police helicopter pilot to distinguish markings of various configurations as well as guidelines for the appearance of the markings and for suitable materials.

2. Covert surveillance systems. A transmitter/encoder affixed to a suspect vehicle generates signals which are received and decoded in a surveillance vehicle. Simple directional circuitry provides a coarse indication of relative bearing and signal strength provides an approximation of relative distance. Systems are marketed by Wackenhut (Bloodhound System) and by WJS Electronics. The Wackenhut system has been employed by the trucking industry for covert surveillance of special cargoes.

CHAPTER V. TECHNICAL CONCEPTS

This chapter examines the requirements of a system to counteract vehicle-related thefts, establishes technical concepts, determines tentative performance characteristics, outlines technical requirements, and considers the cost bounds for implementation.

A. System Requirements

To meet the system objective of materially reducing vehicle-related thefts, a low-cost replacement for the most effective theft prevention measure, surveillance of the vehicle by a security officer, must be found.

A prime requisite is that the system be independent of driver action. Reports[4] show that 60 percent of vehicle-related thefts involve the collusion of the driver and this fact, plus the threat of physical violence against the honest driver, militates against reliance on driver cooperation in theft prevention measures. Similarly, the system must be protected from the driver. Apart from the dishonest driver who will attempt to defeat the system to conceal his theft activities, experience has shown that the installation of any monitoring device is resented as an attempt by management to improve driver productivity, with this resentment often expressed in the form of sabotage.

A police response model (Appendix G) shows that the probability of interception and search time by police vehicles in response to a theft alarm is primarily a function of the diameter of uncertainty of the truck's location. There are three interrelated factors which control this diameter of uncertainty:

- Location of vehicle at time of incident
- Delay in reporting the incident
- Truck speed following the incident

Ideally, to insure interception within a minimum period following the incident, vehicle location must be known, the incident must be reported immediately and the truck speed reduced to zero by a disabling mechanism. Technical and operational considerations in achieving these actions are discussed later in this chapter.

Reduction to a practical minimum of the number of false alarms generated by the system is mandatory. False alarms influence system operation by reducing the number of police vehicles available to respond to a "true" incident and, more importantly, by reducing confidence in the system by both industry and the police. Sources of false alarms fall into two categories:

- Equipment - unreliable components, insufficient protection against external interference sources, incorrect mechanical design of sensors for the vehicular environment, etc., can cause the system to generate false indications.
- Operational - incorrect design of the theft detection logic can result in the generation of false alarms as a result of innocuous activities by the driver and/or freight handler.

The life cycle cost of the system must be commensurate with the per vehicle loss rate of the trucking industry. Further, in order to encourage its implementation, its installation by the industry should result in improved operational efficiencies. However, caution should be exercised in attempting to centralize common system elements to reduce system operating costs for any given urban area:

- The innate conservative attitude of the industry to new "black boxes" will make the simultaneous installation of the system on all fleets in an urban area a highly unlikely event. More typically, one fleet operator will install the system, with follow-on installations by other fleets contingent on the improved competitive edge achieved by the first fleet, or by reports of marked reductions in theft losses from those vehicles equipped with the system.
- Protection of operational data from his competitors is a concern of the fleet operator and, although this attitude could possibly be mollified by designing adequate safeguards, acceptance of such a system could be delayed for a considerable period.

Finally, to insure that the vehicle transit mode of cargo movement is integrated into the monitoring of all cargo when such monitoring is instituted (Cargo Accountability Program), the system should make provisions for the future interfacing of cargo accountability sensors and for the transmission of accountability data from vehicle to base station.

In summary, the system should be independent of and protected from driver action, should incorporate location and other sensors analogous to those of a human observer, should be capable of disabling the vehicle and of discriminating between time and false alarm indications, and should be a cost-effective tool for the industry.

B. Technical Considerations

To translate these general system requirements, a survey of the types of vehicles used in pickup and delivery operations, the types of vehicle-related thefts, and possible detection sensors has been conducted.

The types of vehicle involved are the unit body delivery truck and the articulated tractor trailer, which follow a schedule of pickup and delivery operations, a schedule which may be changed by the dispatcher at the freight depot via a radio communications system.

Vehicle-related thefts fall into two major categories:

1. <u>Theft of the vehicle</u>. This type of theft, that of the entire load, has several variations, but its major characteristic is that time the stolen vehicle is on the public highways is minimized to reduce the probability of interception. The vehicle is driven to a place of concealment, where its cargo is often immediately unloaded for distribution by other vehicles.

a. <u>Hijacking</u>. A typical hijack scenario is portrayed in the film "The Hijackers" produced for the American Transport Association. The cargo vehicle is brought to a halt by armed threat, or by barring its movement by a street barrier or a vehicle. The driver is forced to leave his cab with one of the hijackers driving the vehicle away or, after stopping, is coerced by an armed hijacker in the cab to accede to the directions of the robbers.

Remote sensing of the hijack must incorporate a combination of sensor activation and time sequences such as the following:

- Vehicle is stopped with engine running at non-scheduled stop
- Either cab door has been opened
- Driver's seat is temporarily unoccupied or passenger seat, previously vacant, is now occupied

Note that this sequence of events, although symptomatic of the first stage of a hijacking, may also be caused by innocuous activity, e.g., the driver may stop his vehicle and leave his cab to inspect a tire or the truck may be stopped for a traffic violation. Although this sequence cannot be construed as sufficient reason for alerting the authorities, it should "flag" the dispatcher to an incipient hijack condition, and merits the close monitoring of the vehicle for any of these second stage symptoms:

- Wide deviation from expected route
- Failure to stop at next scheduled stop
- Cargo door open at non-scheduled stop

The dispatcher may elect to establish voice communication with the driver immediately following the manifestation of the first stage symptoms in an attempt to clarify the situation. Lack of communication would provide strong suspicion of a hijack. Similarly, comparison of actual vehicle location to that reported by a driver would provide a further clue to the situation.

b. Theft of unattended vehicle. Thefts of unattended vehicles occur both from freight depots and from open parking lots. The task of the thief is simplified by the fact that many vehicles have the ignition key replaced by a toggle switch. Thefts are not limited to vehicles ready to be driven away: an experienced driver thief can couple a tractor to a parked trailer in less than three minutes. Again, the characteristic of this type of theft is minimum time on the public highways.

In the case of theft of the vehicle parked on the street or in an open parking area, such as a truck stop (where the driver may have been paid to take an extended coffee break), sensing of anomalous vehicle activity similar to that of hijack detection is required:

- Wide deviation from expected route
- Failure to stop at next scheduled stop
- Cargo door open at non-scheduled stop
- Communication or lack of communication with the driver

Theft of rigs or trailers from the freight depot is not unusual, and the type of sensing elements described above can provide a theft alarm. In addition, a vehicle motion sensor to alert the dispatcher to the movement of a vehicle within the depot can provide further protection. In order for the vehicle to move freely within the area for loading or unloading purposes, this sensor would permit limited movement of the vehicle prior to transmitting an alarm. Use of this additional information would require that the dispatcher be aware of the vehicle's arrival, or its readiness to depart the depot with an authorized driver in the cab.

2. Thefts from vehicles. The theft of one or more cases/cartons of merchandise from cargo vehicles constitutes the major source of loss in the trucking industry.

Thefts from vehicles fall into two major categories:

a. After-hours break-in. Loaded vehicles and trailers parked overnight within a freight depot are the target of cargo thieves. Entry into the cargo compartment is generally via the cargo door after disposal of the easily defeated padlock, although entry through the sides or top of the vehicle may be made to avoid alarm mechanisms. An intrusion detector located within the compartment, a vibrator detector or an impedance detector can provide warning of illegal entry. The principal requirement is that of positive detection without false alarms caused by nearby traffic, wind, etc.

b. Thefts during normal operations. Vehicle-related theft activity during normal pickup and delivery operations manifests itself in two ways:

- Part of the authorized load is delivered directly to the fence or to an unloading dock where a cooperative freight handler will use other vehicles for its distribution
- The vehicle will be used to distribute previously stolen goods.

Detection of these activities at other than scheduled stops may be accomplished by sensing the opening of the cargo compartment door at other than previously authorized pickup and delivery stops. Theft of goods at a scheduled stop or distribution of stolen goods within a network of such scheduled stops should be detectable when the cargo accountability system is integrated with the cargo security system.

In summary, detection of theft activities may be accomplished by the installation of position location sensors, cargo compartment access sensors, and driver activity sensors on the vehicle, and by communicating these data to the dispatcher for interpretation, verification and subsequent action.

The desirability of a vehicle disabling capability is a subject of much debate. From the carriers' point of view, recovery of the cargo is of prime importance and disablement can immeasurably improve the probability of recovery. There are some reservations, however, as to the reaction of the hijackers against the driver should disablement be employed. The law enforcement attitude is that apprehension of the perpetrator can be accomplished more readily if the vehicle is tracked to its destination, and therefore vehicle disabling should not be employed. There is general agreement that automatic disabling as a function of sensor data should not be employed, but that disabling action be under the manual control of the dispatcher or security officer.

C. Performance Characteristics

1. <u>Vehicle location accuracy</u>. Ideally, locating the position of the truck on a specific street is desirable for interception purposes. This location accuracy implies a 100 foot (width of street) diameter of uncertainty. However, a response model (Appendix G) has demonstrated that because of many variables, response time cannot be significantly increased when the truck's diameter of uncertainty is less than 1000 feet, (i.e., a location accuracy of 500 feet), providing that the truck's speed is below 20 miles per

hour. Another factor in the determination of location accuracy is the police detection diameter, the line of sight between the police vehicle and the truck, but this factor is minor when the truck's diameter of uncertainty is less than 1000 feet due to the fact that the horizontal line of sight in a high-rise grid type urban area is limited to one city block (approximately 600 feet). At truck speeds greater than 20 miles per hour, a decrease in uncertainty of diameter can measurably improve response time, but the circumstances which permit these greater speeds, e.g., low density population areas or expressways, also permit a wider diameter of detection by the police vehicle. It is concluded that for cargo security purposes, a location accuracy of 600 feet will be adequate until police response time can be significantly improved.

The installation of location sensors on board police vehicles has been shown[6] to improve response time to an incident, and a higher accuracy for truck location may be desirable in the future. Consequently, it is recommended that in designing the location sensor for the near-term requirement of 600-foot accuracy, a design goal of 300 feet should be established.

2. False alarm rate. The influence of Mean Time Between False Alarms (MTBFA) on police utility has been modelled (Appendix G) and shows that an MTBFA of more than one per week does not significantly affect utility. Effects on police morale of a high rate of false alarms must, however, be considered in establishing this parameter. The dispatcher tends to act as a filter of false alarms and it is considered that an MTBFA of one month for each vehicle is adequate.

3. Dispatcher alarm logic. The earlier discussion of the potential countermeasures to the various categories of vehicle theft showed that data from the vehicle sensors needs to be combined and/or compared with predetermined parameters to provide the dispatcher with an alert or alarm condition. Simple combinatorial logic can provide many of these "flag" indications; for example:

- Vehicle stopped plus changes in cab occupancy
- Vehicle exceeds x feet of movement within depot limits
- Cargo door open or intruder in cargo area when vehicle is parked overnight
- No communication with vehicle within x minutes

Position comparison is key to many alert or alarm conditions. Basic alarm conditions include:

- Cargo door open at unauthorized stop
- Failure to arrive at scheduled stop within specified schedule
- Wide deviation from expected route

It is important to note that route and time deviations are not intended to necessitate the use of scheduled routes for system operations. Rather, they are intended to provide a "window" which allows for traffic problems, route detours and a tolerable latitude of driver preference.

Lack of communication capability with the truck is significant in that the vehicle's communications antenna is the one element in the system most vulnerable to sabotage. Loss of communications capability prevents the dispatcher from monitoring vehicle status, and consequently early warning of the loss is mandatory if successful interception is to be achieved. Reaction to this warning must be tempered by recognition of the fact that there will be areas of a city where no communications are possible, as for example in a tunnel. Consequently, the dispatcher alarm logic must be capable of comparing vehicle position with locations of known communications blackout.

4. Vehicle monitoring rate. The rate at which the position and status of each vehicle is reported to the dispatcher is constrained by the data rate of the communications link. Use of the fleet's existing mobile radio communications system is desirable to maintain operating costs within the established economic limits. It has been determined that existing systems can handle approximately 300 bits/second digital data on the channel, and experience has shown that 50 vehicles per channel is a common operating ratio. It should be noted that many of the transactions on truck communications channels are for the purpose of querying truck position, and elimination of this traffic by the installation of a location system would increase the available digital data capacity.

It would appear that to have the vehicle report changes in sensor status only would reduce channel traffic to a minimum. For example, the opening of a cargo door would result in the initiation of status and location transmission to the dispatcher for verification of schedule, and provide for recognition of alarm conditions in adequate time to initiate response action. Similarly, regular reporting of vehicle position, perhaps at a rate governed by the speed of the vehicle, should provide sufficient data for position comparison checks.

However, it must be recognized that loss of communications between the vehicle and the dispatcher results in loss of vehicle position data, and any delay in initiating response action will increase the truck's diameter of uncertainty, with a corresponding decrease in probability of detection by police vehicles. It has been established (Appendix A) that a communications antenna in a concealable configuration is feasible; however, the possibility of electromagnetic shielding of the antenna by the perpetrator cannot be discounted, although this is not expected in the near term. It is essential therefore that communications integrity be verified at an interval which keeps the diameter of uncertainty within reasonable bounds, yet maintains the total fleet digital data rate within channel capacity.

A further factor to consider in establishing vehicle monitoring rate is the advisability of closely monitoring a vehicle which manifests symptoms characteristic of an incipient theft situation. Only a small number of vehicles would be expected to be under this close surveillance at any given time.

Appendix B, which examines the tradeoff between on-board and base station computation of vehicle location, concludes that a 300 bits/second link is theoretically capable of handling up to 100 vehicles, 90 of which are monitored at a 30-second interval and ten at a six-second interval. However, the practical aspects of implementing high update rates, message protocol, base station processing, dispatcher saturation, etc., must be considered. There is a dearth of practical experience at this time, and field evaluation testing is required to establish reasonable limits. Initially, it is considered that a monitoring interval of one minute in the surveillance mode and of 15 seconds in the alarm mode is adequate. These intervals, assuming an average speed of 15 miles per hour, will result in diameters of uncertainty of 4200 feet under communications loss conditions, and of 1950 feet under all other alarm conditions.

D. Technical Requirements

The technical parameters have been translated into a set of general technical requirements for the system. In determining these technical requirements, freight carrier operations have been analyzed, state-of-the-art components identified, and assistance has been been sought from security and operations personnel in the trucking industry.

1. Vehicle system.

- Installation. The vehicle unit should readily interface with existing vehicle equipment and require minimum 'out-of-service' time for its installation.
- Environment. The vehicle unit should be capable of withstanding the temperature and vibration extremes encountered in cargo vehicle operations.
- Protective Measures. The vehicle unit should contain sensors which detect unauthorized tampering: removal of the unit, severing of interface cables, etc. A self-contained battery, capable of supplying sufficient power to transmit an alarm signal, should be an integral part of the vehicle unit. A concealed antenna is desirable.

- Sensors. The vehicle system should provide as a minimum the following sensor capability:
  - Location to an accuracy of 600 feet with a confidence level of 95 percent. Accuracy to 300 feet is desirable.
  - Vehicle movement with provision for eliminating false reports due to the disturbance of the vehicle by high winds, etc.
  - Cargo compartment access to provide positive indication of human entry, and with a high false report rejection capability.
  - Driver cab access to provide indications of door openings and changes in seat occupancy.
  - Data control - the vehicle unit should contain the means for formatting sensor inputs and vehicle identification codes for transmission to the base station, and for responding to interrogations from the base station.
  - False alarms - must occur at less than one month intervals.
  - Signal distribution - interface between the elements of the vehicle system should preferably utilize the existing vehicle wiring, with provisions made for the elimination of false data generated by external vehicle components.

2. Dispatcher system.

- Vehicle polling. The base station unit should have the capability of polling vehicles on a selective automatic or semi-automatic basis. Polling rate should be adjustable on an automatic or manual basis to provide for a 60-second update of all vehicles in the fleet and for a 15-second update of selected vehicles.
- Route comparison. The base station should provide comparison of vehicle position with expected routes between authorized stops, provision being made for variation of alarm tolerance limits by the dispatcher.
- Sensor logic. The base station should contain logic to combine sensor data received from the vehicle units into warning or alarm signals. Provisions should be made to permit variation in logic/time sequences to meet specific operating procedures.
- Position display. The base station should provide display of vehicle position in a form readily translatable to geographic coordinates.
- Remote alarm. Provisions should be made for alerting security guards to attacks on vehicles within a depot security perimeter during periods when the dispatcher station is unmanned.

E. Costs

The cost analyses of vehicle-related theft discussed in Chapter III indicate that a cargo security system would be cost effective to the trucking industry with total system operating costs in the order of $1000/year/vehicle. This section examines the alternatives in maintaining this cost limitation and establishes practical cost bounds for the system.

Total operating costs of a cargo security system include the following:

- Vehicle unit
- Vehicle unit installation
- Vehicle unit maintenance
- Base station
- Base station installation
- Base station maintenance
- Base station operations
- Location system
- Location system installation
- Location system maintenance
- Location system operations

A cost model has been developed to determine the basic bounds of the system. For model purposes, the following assumptions were made:

- Vehicle unit life = five years
- Vehicle unit maintenance = vehicle unit cost

- Ground support equipment life = ten years
- Ground support equipment maintenance = ground support equipment cost

Figure 5 presents the basic cost bounds for a $1000/year/vehicle system for various fleet sizes. Although there appears to be a wide range of feasible combinations of vehicle and ground support equipment costs, restrictions are imposed by an examination of practical constraints:

- There will be a minimum vehicle unit cost, irrespective of the location technology employed, of sensors, interfaces, data controller, and installation. This minimum cost is estimated at $400.
- Operating costs of the base station, although amortized over the entire vehicle fleet, significantly influence the per vehicle cost. The cost to the trucking company of a full-time system operator could be in the order of $30,000 per year, assuming that a single operator could integrate the inputs from the various dispatch operations. For a 50-vehicle fleet, this cost would result in a per-vehicle cost of $600/year. To eliminate the need for this operator, sufficient logic must be designed into the base station to enable system operation to be accomplished by the dispatcher. Depending on the degree of sophistication desired, the cost of equipment to perform this function will range from $10,000 to $50,000 for a fleet size of 50 to 100 vehicles. For small

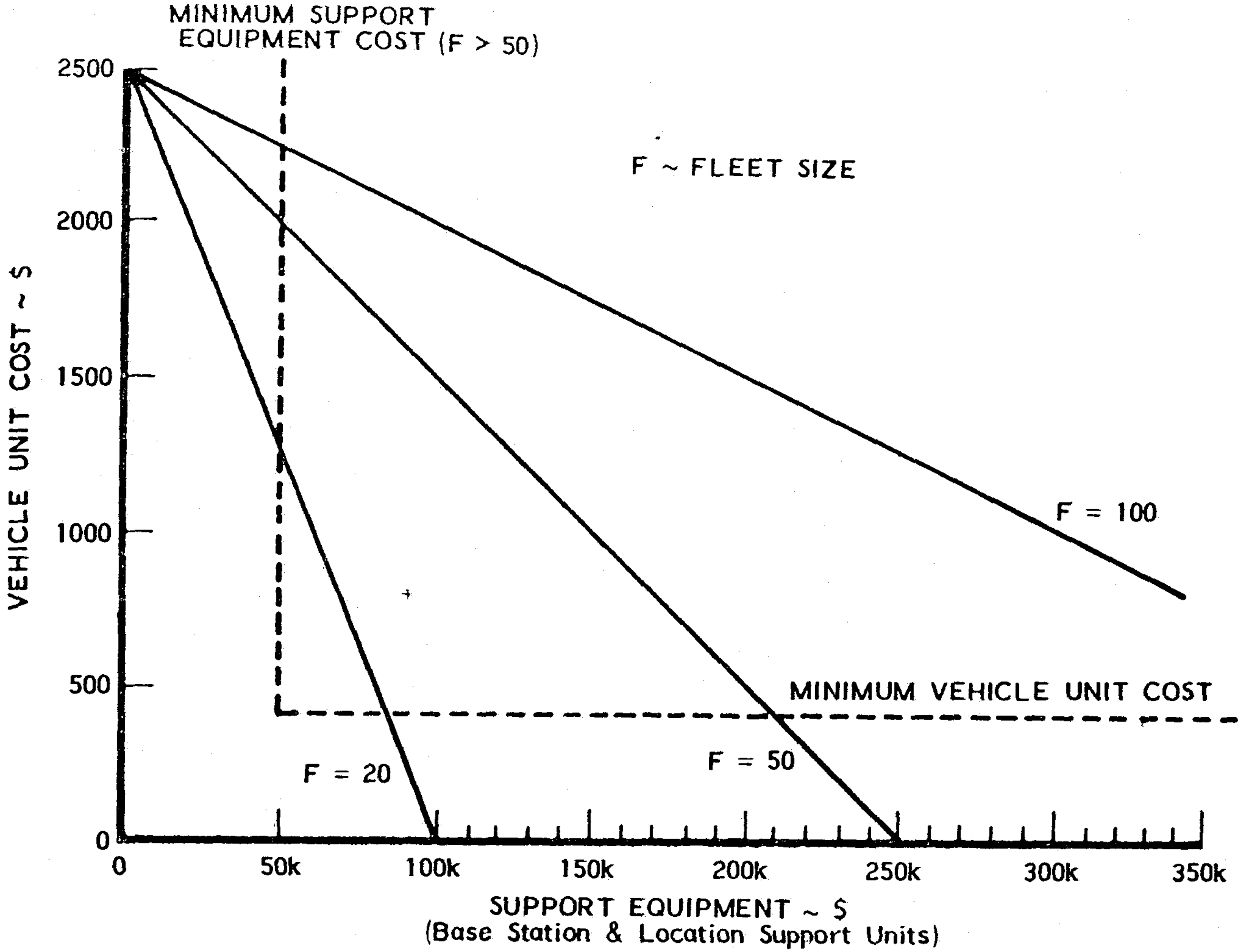


Figure 5. System Cost Limits

fleets (10 to 20 vehicles) where the dispatcher workload is not severe, simpler equipment may suffice.

- Ground support equipment for the vehicle location system must be capable of automatic operation, the cost of operations personnel being prohibitive.

An upper bound to the cost of the vehicle location sensors is imposed by data communications requirements. Appendix B examines the data rates required to provide the base station with the requisite information for its operation. Should an additional data communications system be required in each vehicle, its cost must be included in the cost of the vehicle unit.

CHAPTER VI. VEHICLE LOCATION

The vehicle location sensor is a critical system element. It constitutes a primary indication of vehicle-related theft and provides law enforcement agencies with the means to rapidly intercept the cargo thief. It is the highest single cost element of the system and consequently its selection materially affects the acceptability of the cargo security system by the trucking industry.

The value of vehicle location systems to mass transit and law enforcement agencies has been recognized for several years and the system technology has been the subject of investigations and analyses by private industry and government agencies, a bibliography of which forms part of this report. However, no serious attempt has been made to establish performance characteristics or cost constraints for location systems.

1. Requirements. Requirements for the location system to be incorporated into the cargo security system have been developed in this report. These requirements are summarized:

- Location accuracy. A minimum accuracy of 600 feet, with a confidence level of 95 percent. Accuracy to 300 feet is desirable.
- Ground support operations. Ground support elements of the location system should require no operating personnel.
- Operating costs. Total system operating costs of the location system alone should not exceed $640/year/vehicle for a fleet of 50 vehicles, operating in an urban area of 500 square miles.

- Data privacy. The location system should not rely on a shared central data system for its operation.

2. Survey of existing technology. Existing location technology can be categorized into four major areas:

a. Proximity systems. Proximity systems are roadside units which provide location data. Located at intervals commensurate with the position accuracy desired, the system can determine absolute vehicle location. Proximity systems are classified into two categories:

(1) Direct proximity. The roadside unit transmits location data to the passing vehicle, which retransmits these data, together with the vehicle identification code, to the base station.

Many technologies have been explored, including acoustic and optical signals; however, the two systems which appear most practical are RF systems and magnetic systems.

In the RF system, the location data is transmitted in digital format to a receiver on the vehicle. Selection of the transmitter frequency and power is highly critical and is discussed in Appendix C. Installation and maintenance costs are significantly influenced by the manner in which the proximity units are powered. Connection to local utility power lines may involve a considerable installation cost (current estimates: $8/foot of conduit should local codes require its use) and there are many instances, e.g., along high speed freeways or turnpikes, where utility power is not available. Batteries capable of powering the transmitter are available. Long-life batteries are desirable to reduce maintenance costs, and Appendix D examines the battery types suitable for this application.

Transponder-type units, which derive their power from the energy transmitted from a vehicle-mounted interrogator, offer a promising solution to the problems of active transmitters. However, selection of frequency and power of the interrogator is critical, in that range must be limited to the nearest proximity unit and obstruction of line-of-sight between the vehicle and the proximity unit may interfere with operation.

The magnetic system employs magnetic patterns imbedded in the road surface to provide a unique location signal to a detector unit mounted on the underside of the vehicle. This is a simple system in that no power is required for the road elements and the detector unit contains no complex RF components. The fact that a vehicle must pass over the magnetic pattern requires that the patterns are located such that all highway lanes are equipped, lane changes are accommodated, and, for emergency vehicle use, location data is obtained when the vehicle uses the counterflow lanes. Maintenance of the magnetic units is essentially zero, but reinstallation of the patterns is required following road repairs or major resurfacing activities.

(2) Inverse proximity. Vehicle identification is transmitted by the vehicle to the roadside unit, which relays this identification plus its location to a base station via conventional ground communications equipment. Optical and RF technology is employed in current location systems. The principal drawback of the technologyis the cost of linking each roadside unit to the base stations, particularly in cities encompassing large areas; for this reason, its use has been confined to constricted, fixed route systems such as railroads, bus systems, and toll collection barriers.

The location accuracy requirement of the cargo security system would require a high density configuration (total of 50,000 proximity units to provide 600-foot accuracy in a 500-square-mile area). To meet the cost requirements defined for this system, the installed cost per proximity unit would have to be no greater than three dollars, assuming a per-vehicle location sensor cost of $50, a clearly impractical situation.

The use of proximity units in a low density configuration to support other location systems can, however, provide significant benefits and is reviewed in subsequent sections of this report.

b. Hyperbolic systems. Measurement at a vehicle of the time difference of arrival of signals from three or more transmitting stations establishes two lines of position on a hyperbolic grid. Employed for many years for marine and airborne navigation, hyperbolic systems have been considered for land-mobile use.

There are three principal contenders:

(1) Decca navigator. Designed for ship and airplane navigation in the North Sea and Baltic, this British system has been successfully tested in both New York and California for local air and marine navigation. No thorough testing of its performance on ground vehicles in an urban environment has been undertaken. The system employs a minimum of four special purpose transmitting stations in a 'star' pattern. Discarded by the U.S. Coast Guard in favor of Loran-C, there are no plans to establish a permanent U.S. network.

(2) Loran-C. This system employs a triad of special transmitting sites. Tests conducted with this system during the Philadelphia vehicle location evaluation[7] showed an accuracy capability of 2100 feet. Subsequent tests by the manufacturer have reputedly improved this figure to 721 feet. Loran-C coverage is currently restricted to the East coast of the U.S. However, the U.S. Coast Guard is seeking Congressional funding to provide additional transmitting sites in the 1976/1978 time period.

(3) Omega. The principal navigation system for the U.S. Navy, Omega employs high powered, low-frequency transmitters to provide worldwide coverage. The accuracy of the system is subject to wide diurnal variations which are capable of being corrected by computer-generated data. To reduce mobile unit costs, differential Omega can be employed. In this system, correction data is computed at the fixed base to update the raw data received by the vehicle. Claimed accuracy is 500 feet in an offshore marine environment, but data from the Naval Electronics Laboratory indicates a more realistic accuracy of 2400 feet.

All RF hyperbolic systems are subject to severe fading problems in certain urban environmental conditions (e.g., within tunnels), in the vicinity of railroad tracks, etc., and employment of such a system would require installation of supplementary location aids.

c. Dead reckoning systems. Measurement of direction and distance travelled between changes of direction provides location relative to a known starting point. The two basic components are a direction sensor and a distance travelled sensor (Appendix E).

The magnetic compass supplies a direction reference and is available in static form, i.e., a solid state element not subject to acceleration forces. Three principal sources contribute to errors in the compass:

- The local magnetic variation of the earth's magnetic field is supplemented by man-made structures to form a complex variation pattern. Bridges, tunnels, railroad tracks, and buildings contribute a modification to the local earth's field.
- Deviation due to the environment immediately surrounding the sensor can be both static and dynamic. A tool box, spare wheel, tire chains, etc., in the vicinity of the compass, are contributors to the static deviation. Operating car radios, airconditioning units, etc., form the dynamic deviation components.
- The presence of large vehicles in the vicinity of the compass-equipped vehicle forms random variations of the magnetic field. Buses and garbage trucks have proved to be particularly large contributors to dynamic magnetic variation.

The distance measurement sensor is a counter, actuated by the vehicle odometer drive or by a wheel sensor. Because of rear-wheel slip, a front wheel has been identified as the optimum location for the sensor. Errors can be categorized into two areas: sensor and environmental. Sensor errors are introduced by variations in the circumference of the wheel resulting from variations in tire inflation pressures. Environmental errors are caused by wheel slippage (front wheel skid or slip due to road camber) and by turns.

Methods of compensating for these errors fall into two categories: vehicle sensor calibration and position correction.

(1) Calibration. Magnetic deviation due to elements within the vehicle is measured by "swinging" the vehicle and obtaining calibration data. Similarly, systematic errors due to wheel size can be measured at nominal tire pressure for entry into a correction algorithm.

Because of changes caused by changes in the magnetic variation of the vehicle due to different loads, and in tire pressures during normal operations, calibration must be performed at frequent intervals to be an effective means of compensation.

(2) Position correction. A prototype dead reckoning system, manufactured by Boeing/Wichita for police applications, corrects for compass deviations and wheel turning distance errors by "mapping" the area of operations in a computer memory. The computer map describes the geographic coordinates of the city streets and locations of known magnetic errors. As sensor data are received from the vehicle, the computed position is compared with the city map and corrections applied to adjust the location to its most probable street position (Figure 6).

Correction of positional errors due to distance sensor errors can be accomplished in a similar manner, providing that the vehicle makes turns at frequent intervals. A long period between turns can introduce ambiguities leading to major errors.

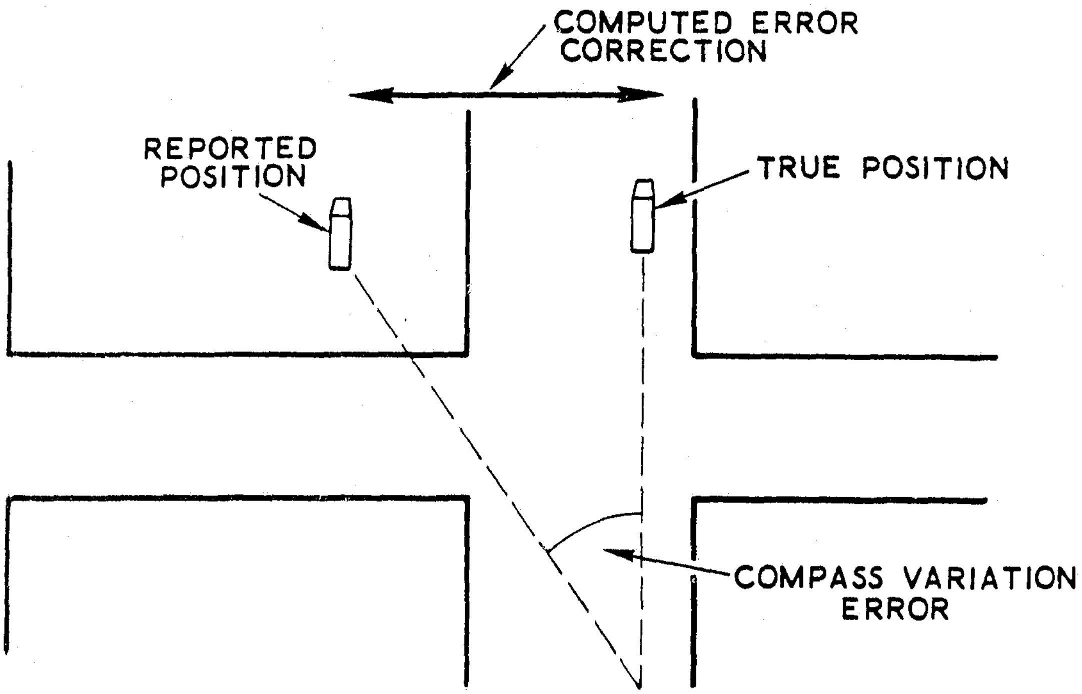


Figure 6. Position Error Correction

Figure 7 illustrates this situation. With an error rate of 0.5 percent (a conservative number), a vehicle travelling without turns for ten miles would accumulate a 300-foot distance error. After making the turn, computer mapping, in attempting to relocate the vehicle to the nearest street, could introduce a position error of 600 feet (average city block).

In order for the computer to execute the filter algorithms to meet system accuracy requirements, data from the vehicle must be reported at a rate sufficient to provide short term corrections. Large intervals between data transmissions can introduce major position errors. For this reason use of computer mapping techniques for position correction requires a high data rate between vehicle and base station (Appendix B).

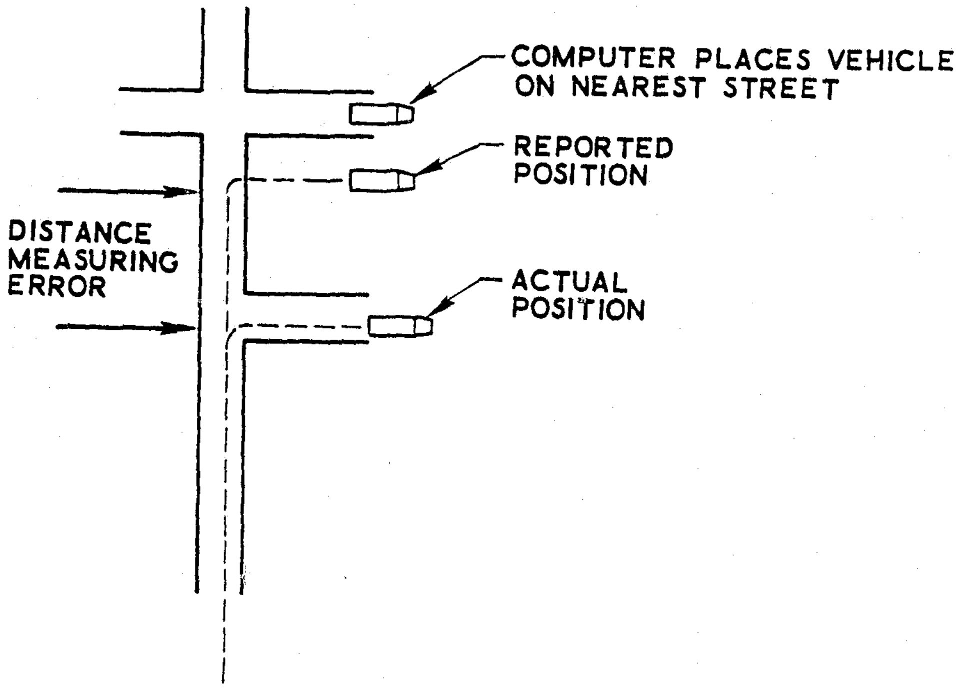


Figure 7. Effect of Distance Measuring Error

One other dead reckoning system is currently in use. A military system in use by the UK/NATO military forces, the Sperry Navigator, is a self-contained inertial system incorporating a computer. Its cost ($12, 500 in quantity) precludes its use for commercial applications.

d. Triangulation/multilateration systems. Fixed sites, strategically located in each area of operations, receive vehicle transmissions and resultant data provide vehicle location at a central computer.

Triangulation systems determine the bearing of the vehicle from fixed sites. The bearing data is transmitted to a central location for the computation of position. Multipath effects, particularly in high-rise areas, introduce significant errors into the computation.

Multilateration systems determine the distance of the vehicle from each fixed site and the central computer determines actual location. Multipath path effects are small compared to the triangulation system. Pilot tests in New York City have demonstrated a 500-foot accuracy capability.

Both types of system are subject to the environmental fading associated with large area RF systems. Each system requires the installation of special transmitter/receiver sites at selected locations throughout each city, linked by landline to a central computer system.

3. Potential location systems. Analyses performed at The Aerospace Corporation have identified location technologies having the potential to meet the cost/performance requirements of the cargo security system. These analyses have shown that no stand-alone technique can adequately meet the requirements, but that combinations of technologies can provide the trucking industry with an effective location system.

Two systems are described: a hybrid dead reckoning unit and a hyperbolic system based on existing AM radio stations. Each system relies on supplementary proximity units deployed in a low density configuration to correct inherent errors.

a. Hybrid dead reckoning. As described in the previous section, the disadvantages of a compass/distance measurement technique are magnetic deviations and variations, plus accumulated distance errors.

The magnetic compass provides reasonably accurate long-term characteristics for dead reckoning purpose. However, its short-term characteristics make it unsuitable for this purpose unless extensive support elements, such as computers, are employed. To obtain accurate short term data, inertial components can be utilized. These components have excellent short-term performance, but have long-term drift characteristics. Analyses have shown that a combination of a magnetic compass and inertial components can provide a smoothed azimuth component of a dead-reckoning system.

To supplement dead-reckoning components, a low density proximity system can be employed. Employment of proximity units provides the dead reckoning system with:

- Accurate position updates when the vehicle is passing the proximity unit
- A means to dynamically compute the error rate due to inertial component drift and distance measurement, and to adjust for these error rates in the on-board unit

Such a hybrid system would enable position to be continuously computed on board the vehicle, thus reducing the need for a high rate data link and a base "mapping" computer. The cost of computing elements suitable for this purpose is commensurate with the vehicle unit cost bounds.

b. <u>AM phase lock</u>. The availability in all metropolitan areas of high level signals from local AM broadcast stations has led to consideration of using these signals as a means of vehicle location.

The use of direction-finding equipment on the vehicle has been proposed on many occasions, but an extensive evaluation conducted by The Aerospace Corporation has shown that multipath effects from local structures preclude the use of this technique in urban areas.

The use of three or more AM stations to form a local hyperbolic grid is reviewed in Appendix F. Compensation for the drift rate permitted by the FCC for AM broadcast operations can be made in one of two ways:

- Installation at the base station of a relative phase error measuring system, the output of which would correct the data received from the vehicle
- Installation of equipment at the broadcast stations to ensure phase stabilization of the signals

Analyses have shown that the most cost effective approach is to modify the broadcast stations. An atomic standard replaces the crystal oscillator in one station (master) to provide a frequency stability of better than 1 part in 10^{11}. Phase lock equipment installed at the remaining stations receives (slaves) the signal from the master station and generates an excitation signal phase-locked with the master.

The vehicle equipment would consist of three receiver units whose combined outputs would provide data describing intersecting lines of position.

Because such a system is a relative positioning system (i. e., position is known from a predetermined starting point) and because of signal fade conditions under certain conditions (under bridges, in tunnels, etc.), a reset mechanism is considered essential. This reset mechanism would consist of proximity units, located in a low density configuration in areas of known fading and often used checkpoints (freight depots, highway freight checkpoints, etc.).

4. Future systems. A location system based on multiple satellites in synchronous orbit is currently under development by the Department of Defense. Projected system accuracies are much higher than those identified for any vehicle location application. Channels for commercial users are planned in the system, which will be available within eight years if the current schedule and program funding are maintained.

CHAPTER VII. DEVELOPMENT CONCEPTS

As a result of surveys and assessments of the cargo security problem and current theft prevention measure systems, it has been determined that there are no extant systems which are cost effective for the trucking industry. Cost bounds for such a system have been established and potential subsystems and components have been identified. A cohesive development plan has been established to fully define an integrated cargo security system.

A. Studies and Analyses

Three major areas of study and analysis will support the establishment of system requirements.

1. Performance requirements. This task will establish the overall performance requirements of the system in terms of

- Theft alarm criteria
- Location accuracy
- False alarm limits
- Location update interval
- Dispatchers' data requirements
- System reliability

2. Technical constraints. The technical constraints associated with the system will be identified:

- Vehicle unit environmental constraints
  - Shock
  - Temperature

  - Humidity
  - Electromagnetic interference
- Vehicle unit physical constraints
  - Size
  - Weight
  - Power
- Vehicle unit installation constraints
  - Physical location
  - Wiring
  - Tractor/trailer disconnects

3. <u>Support requirements.</u> System support requirements will be investigated:

- Impact of FCC regulations
- Impact of state, county, and municipal codes
- Compatibility with public safety vehicle location systems
- Maintenance methods
- Technical and operating personnel training programs

B. Hardware Development and Test

To obtain operational data upon which to base system requirements, installation of a brassboard system in a limited number of road vehicles and their associated dispatcher station is considered essential. The purpose of this installation will be to demonstrate system concepts and to evaluate system performance, and, for this reason, the units need not be developed to meet the environmental and physical characteristics established by the technical studies. The task of design, development, fabrication, and evaluation will be accomplished over a 16-month period.

In support of this task, continued investigations and breadboarding of candidate low-cost vehicle location technology will continue. Emphasis will be placed on technology which does not rely on centralized data systems, i.e., systems necessitating the involvement of other users to ensure implementation by the trucking industry. The vehicle location requirements for trucks are commensurate with those of public safety vehicles, and the concept development of this technology will consider its applicability to police operations.

C. Conclusions

At the completion of this program of studies, analyses, hardware development, and evaluation testing, it will be possible to quantitatively determine:

- The performance of the system as a vehicle location and status monitoring device
- The efficiency of the system in trucking operations:
  - Reduction of theft incidents on trucks equipped with the system
  - Improved driver performance
  - Improved dispatch operations
- Needs for added features

From these data, a detailed system specification will be developed to enable units for a full scale field test to be defined.

APPENDIX A. A LOW-PROFILE ANTENNA

A loop-monopole antenna was investigated as a possible alternative to the conventional quarter-wave monopole whip antenna commonly used for voice communications on commercial and police vehicles. The loop-monopole has the advantage of low physical profile and can be concealed so as to be less vulnerable to being rendered inoperative in the event of physical attacks by assailants.

The loop-monopole antenna is shown photographically in Figure A-1, and schematically in Figure A-2. The antenna consists of a 5.29-inch diameter (C-C) loop spaced 1.0 inch over a ground plane. One side of the loop is grounded, and the open end of the loop has a variable capacitor to ground which tunes the antenna to resonance at any frequency in the 150- to 170-MHz band. The coax feedline is connected 2.75 inches from the grounded side of the loop to achieve the best impedance match.

Radiation from the antenna is predominately vertically polarized with the ground plane in a horizontal plane. The vertical fields are generated by currents on the center conductor of the coax feed, the short conductor between one side of the loop and the ground plane, displacement current through the tuning capacitor and from the electric field between the loop and the ground plane. A second capacitor (C_1) is added in series with the center conductor of the feed line to provide a convenient means for adjusting impedance to a 50-ohm level.

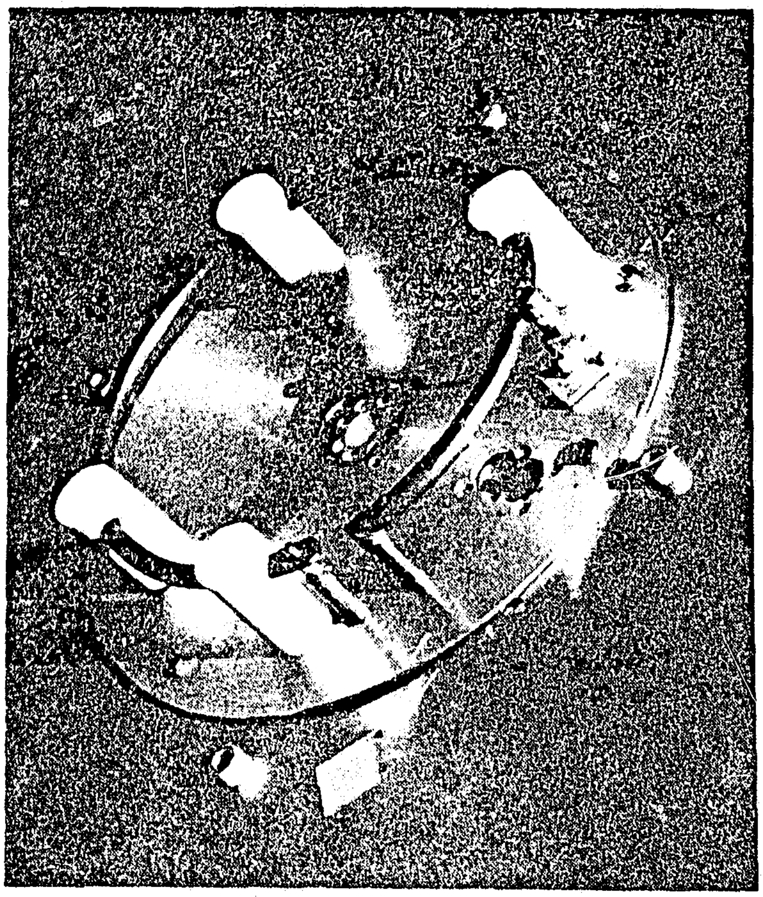


Figure A-1. Photograph of Loop-Monopole Antenna

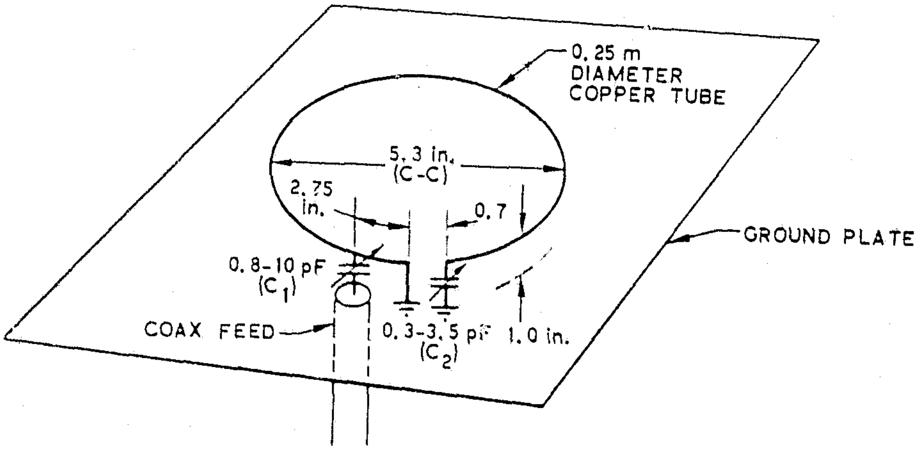


Figure A-2. Schematic of Loop-Monopole Antenna

Patterns were measured with the antenna assembly mounted on the roof of a 1969 Ford panel truck, providing a ground plane approximately 67 x 134 inches (0.9 x 1.8). The relative heights of the loop-monopole and corner reflector resulted in an azimuth pattern cut 3.7 degrees below the horizon. The pattern was measured at midband, 160 MHz, and results are shown in Figure A-3. For comparison, a pattern of a $\lambda/4$ vertical monopole mounted at the same location on the vehicle and with the same power input is included in the pattern plot, thus providing relative gain between the two antennas. Prior to pattern measurement VSWR values were as follows:

- Loop-monopole: VSWR = 1.34
- $\lambda/4$ monopole: VSWR = 1.40

Examination of Figure A-3 shows that the loop-monopole gain is from 1.0 to 2.0 dB or, as an average, 1.6 dB below that of the quarter-wavelength monopole.

Since the antenna structure is electrically small, it has narrow-band impedance characteristics, as seen by the VSWR vs. frequency plot of Figure A-4. Bandwidth is 2.5 percent, or 390 KHz, between 3:1 VSWR points.

A series of VSWR measurements was made to determine the feasibility of tuning the resonating capacitor C_2 to change the operating frequency within the 150 to 170-MHz band and without tuning the impedance adjustment C_1. Results are given by the VSWR vs. frequency plots of Figure A-5. These results show that only C_2 need be adjusted to cover the 150 to 170-MHz band, and C_1 need be adjusted only for the initial midband tuning.

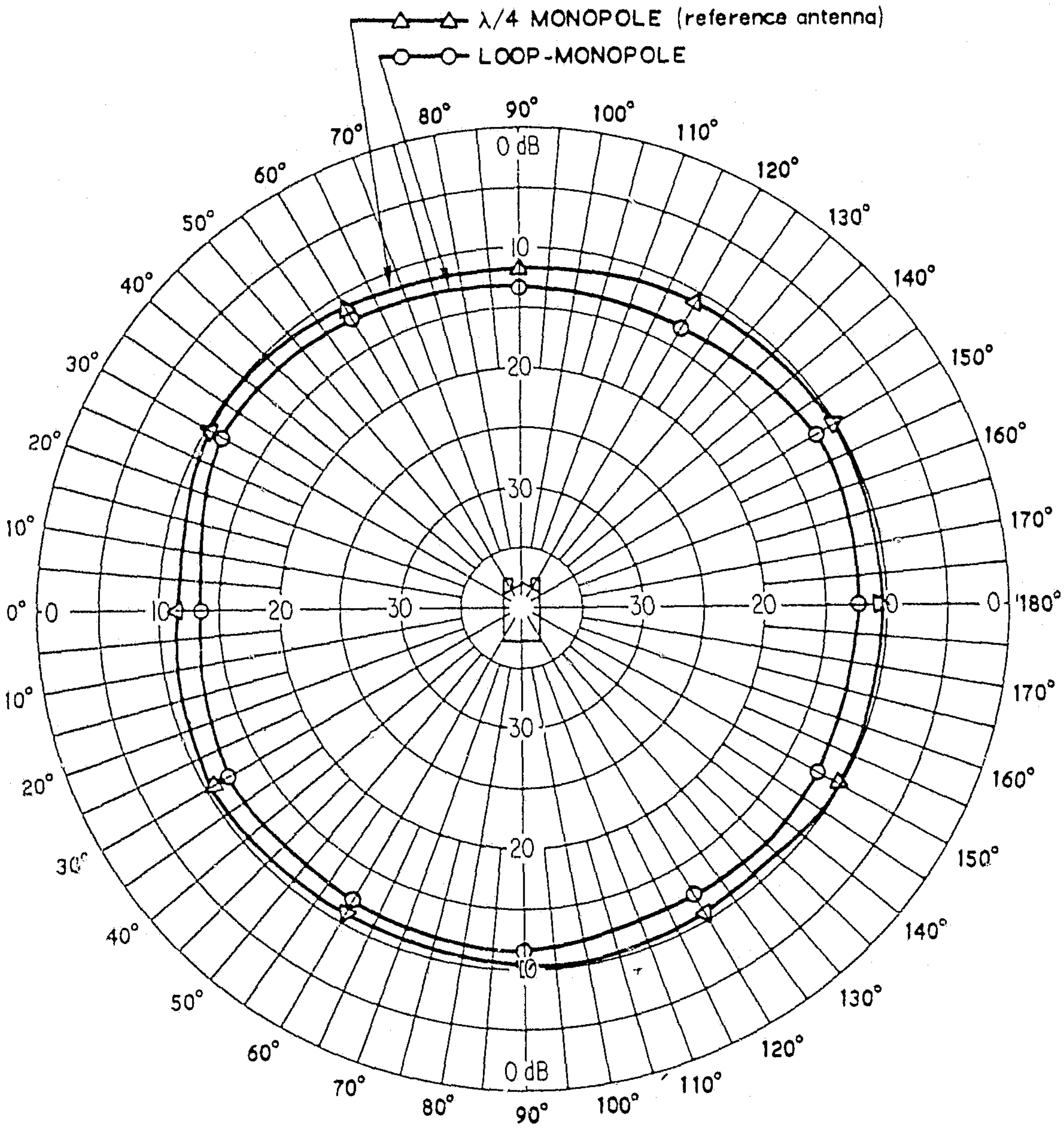


Figure A-3. Azimuth Pattern and Relative Gain of Loop-Monopole Mounted on Roof of Truck

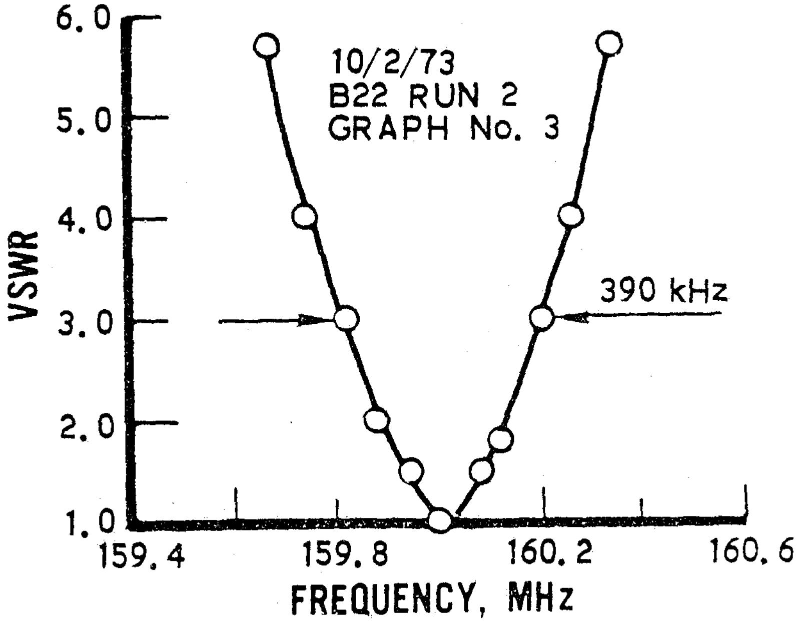


Figure A-4. VSWR vs Frequency of Loop-Monopole Tuned to Midband

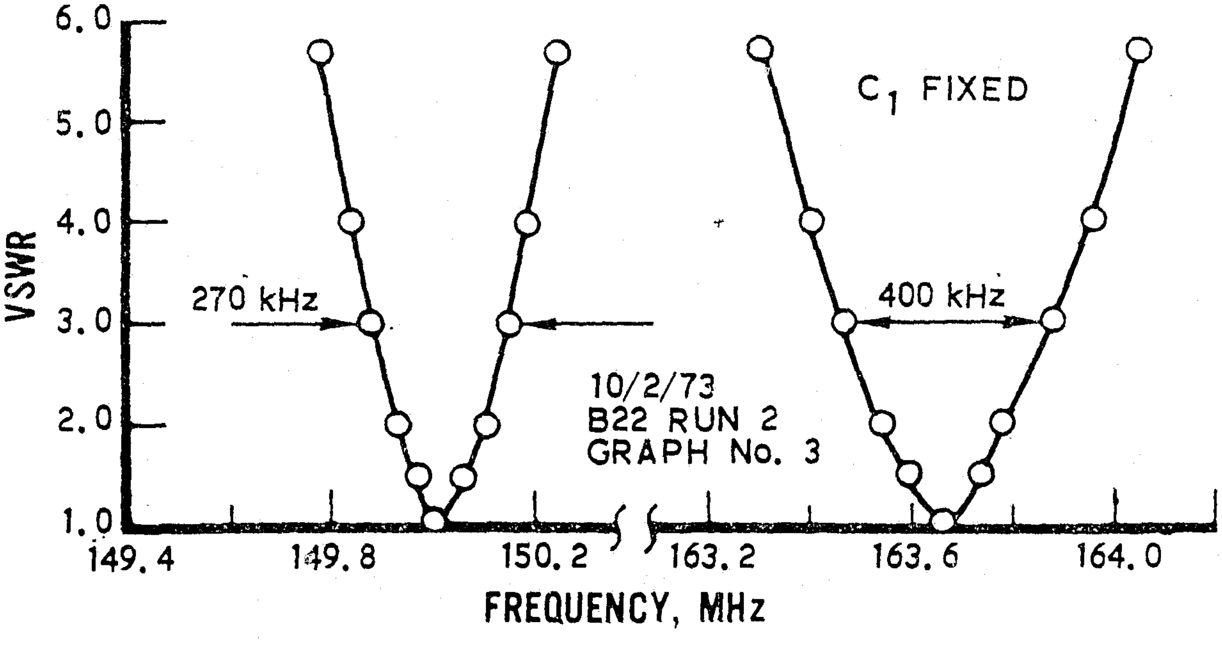


Figure A-5. VSWR vs Frequency of Loop-Monopole Tuned Below and Above Band Center

The results of this investigation show that the loop-monopole mounted on the roof of a truck exhibits good azimuth omnidirectionality (±1.0 dB) and has remarkably good efficiency considering its low profile.

APPENDIX B. DATA PROCESSING LOCATION ANALYSIS

An analysis was conducted of the relative merits of performing the bulk of the data processing for the truck cargo security system either (1) on board the vehicle, or (2) at the central base station. Neither alternative can result in total exclusion of the other. If on-board processing is stressed, there is still a need for sufficient central base processing to provide display data, alarm flags, and adaptive shifting of polling rates in response to alarm flags. If base station processing is used to a large extent, then the vehicle system must provide for distance measurement accumulators with periodic reset-to-zero capability, multiplexing, A/D conversion, encoding data in a serial digital form suitable for transmission, and subcommutation of low rate functions in order to reduce transmission rates.

This analysis was done primarily with a dead reckoning system with periodic updates from a proximity system assumed as the vehicle location system. However, the results apply quite appropriately to other types of location systems such as the hyperbolic system.

Currently, a typical truck-trailer has on board one land-mobile communication set for discretionary use by driver or dispatcher for voice communications. It is intended that this set and its RF link be used by the truck cargo security system to transmit digital data at a rate needed to portray vehicle status and location at the central station. This must be done in a manner which does not disturb the voice communications, but still provides sufficient reliability to permit timely responsive action by the dispatcher when alarm conditions are indicated.

The maximum digital data bit rate that can be used in this sharing of the voice communication set has been estimated at 300 bits/second.

1. On-Board Processing

Azimuth and distance sensor outputs are processed by a microprocessor installed on the vehicle. Location in x-y coordinates and summed status data are transmitted to the base station.

Worst case conditions have been assumed to be with ten percent of the vehicle fleet in an alarm condition, i.e., at a transmission rate of one word/six seconds versus one word/30 seconds under nominal conditions.

a. Data word length

Data Source		No. of Bits in Data Word
Vehicle Identification (256 vehicle system)		8
Location	X	9
	Y	9
(600 feet accuracy in X and Y directions in 20 mile by 20 mile urban area)		
Security Sensors		3
(8 assumed with outputs converted to "alarm" or "no alarm" states)		
Subtotal		29

Data Source	No. of Bits in Data Word
Error Detection	29
General usage of same RF link by many vehicles plus nearby industrial sources of noise raises the probability of noise interference and imposes a requirement for complete error detection.	
Total	58
Roundoff	60 bits/word

b. Transmission Rate (TR). TR is set by requirement to transmit vehicle position to 600-foot accuracy (one sigma) every 30 seconds, and to adaptively shift to every six seconds for those vehicles indicating alarm or anomalous conditions.

Nominal (per vehicle):

$$\text{TR} = \frac{60 \text{ bits/word}}{30 \text{ second}}$$

$$= 2 \text{ bits/second/vehicle}$$

Worst case (with 10 percent of fleet in alarm condition):

$$\text{TR} = \frac{60 \text{ bits/word} \times 0.9}{30 \text{ seconds}} + \frac{60 \text{ bits/word} \times 0.1}{6 \text{ seconds}}$$

$$= 2.8 \text{ bits/second/vehicle}$$

2. All Base Processing

Sensor data are transmitted to the base station with no on-board processing. Computation of location in x-y coordinates is performed in the base station computer.

Transmission rate is governed by the sampling rate required to maintain location accuracy and to avoid ambiguous situations. Figure B-1 illustrates that with error-free sensors, sampling rate is one sample per four seconds. The figure shows a freeway off-ramp transition region. At least one valid sample, "S," must occur in the transition region in order to establish whether subsequent location of the vehicle is at point A or point B. At a maximum speed of 100 feet/second (transition time = eight seconds), a sampling interval of not greater than four seconds is required to positively identify a change in direction.

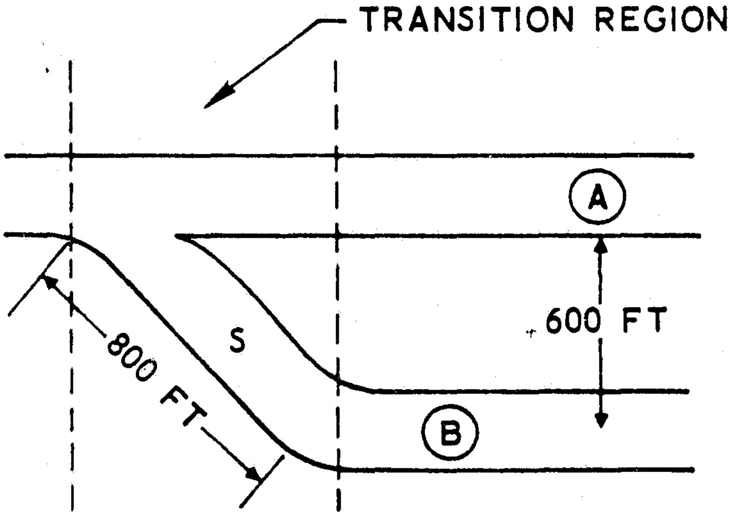


Figure B-1. Sampling Rate Diagram

a. Data word length

Data Source	No. of Bits in Data Word
Vehicle Identification	8
(256 vehicle system)	
Direction	9
(1 degree accuracy in 360 degrees)	
Distance	4
(600-foot accuracy out of 6000 feet with distance accumulator reset every 6000 feet)	
Security Sensors	3
(8 assumed with outputs converted to "alarm" or "no alarm" states)	
Subtotal	24
Error Detection	24
(Same rationale as in on-board processing)	
Total	48
Roundoff	50 bits/word

b. Transmission rate

For nominal and worst case:

$$TR = \frac{50 \text{ bits/word}}{4 \text{ seconds}}$$

$$= 12.5 \text{ bits/second/vehicle}$$

Signpost inputs to bound dead reckoning errors will increase this basic sensor rate as a function of signpost density. For example, with a density of one signpost per mile and a speed of 100 feet/second an additional rate of 0.167 bits/second/vehicle is required.

3. Summary

A data channel of 300 bits/second is capable of handling up to 100 vehicles with on-board processing, but under ideal circumstances the use of all base processing limits the fleet size to 25 vehicles.

For typical fleet sizes of 30 to 50 vehicles, the base processing system requires a digital transmission rate far in excess of the tolerable limit of 300 bits/second. Some relief can be afforded by subcommutation of the distance and alarm sensor measurements but the added complexity of this procedure, along with the other minimum digital data handling on board, indicates that with an additional step (the addition of the microprocessor chips), all location determination processing can be done on board. This permits a transmission rate well within the tolerable limit. The penalties associated with on-board processing include an estimated two watts of added power and less than one pound of added weight. The on-board equipment lifetime is five years, compared to ten years for base equipment.

Despite these penalties, the choice must be made in favor of on-board processing because of lower data rate.

APPENDIX C. PROXIMITY SYSTEMS

Proximity systems in signposts are generally classified as either passive or active. A passive system utilizes receivers at fixed locations to accept information transmitted from vehicles passing a signpost. The location information is then transmitted to the base station via telephone lines or on radio communication links. Each vehicle transmits its identification code. This code is coupled with the signpost location data and is relayed to the base station.

Two factors complicate the use of passive signposts. The first factor results from the situation when more than one vehicle transmitter is in the range of the signpost receiver. The receiver must be sufficiently sophisticated to distinguish each vehicle selectively and accurately. The second factor is related to the requirement for a communication network to relay signpost information to the base station. These factors have militated against the use of passive signpost systems except in special applications.

In an active signpost system, the wayside signpost devices transmit unique identification codes to passing vehicles for subsequent transmission by vehicles to the base station. Each vehicle is equipped with a receiver to accept the wayside post signal as the vehicle comes within range of the signpost. This signal is then decoded and the address of the wayside post placed in the vehicle's memory unit.

Other information can be recorded in the vehicle at the same time that location information is collected. This other information can be the odometer reading of the vehicle when passing the signpost or the time of

CONTINUED

1 OF 2

day. The signpost signal could also be used to re-initialize a supplementary dead reckoning or RF location system. In any event, the location information will be stored in the truck until it is interrogated by the base station or until the truck encounters an "alert" or "alarm" condition.

Methods for signalling between the vehicle and the signpost include electromagnetic radiation (in the form of radio waves, low-frequency induction or optical methods) or acoustic radiation. Acoustic devices tend to be larger and heavier than equivalent radio devices. Also, acoustic devices currently used for traffic sensing are high power and cannot be battery operated. For these reasons, installation would tend to be more expensive than the alternative radio transmission approaches. An additional consideration is that the use of acoustic devices in the vehicle would constitute a "mixing" of technologies, which would unduly complicate the system.

Low-frequency inductive loops are used extensively as vehicle detectors in traffic control systems. The common method of installation is to bury them in the roadbed, however, which makes them unsuitable for trucking company use. Optical methods have generally proven to be unreliable due to such environmental conditions as dirt, fog, ice, and snow. For the requirement of a trucking system, the installation and maintenance problems associated with establishing a signpost system make all approaches other than radio transmission impractical.

Among the factors which affect the design of a signpost device are: range of transmission, frequency of operation, power requirements, modulation technique, data format and false alarm and dismissal rates. Each of these factors will be discussed briefly.

1. Range. The operating range of a signpost is governed by the receiver sensitivity, the required signal-to-noise ratio at the receiver, the allowable output power of the transmitter and such other factors as antenna gain, propagation medium, and noise improvement due to modulation techniques.

2. Frequency. In most cases, the signpost will be radiating at less than 0.10 watts and, therefore, will not require licensing. The frequency will depend upon the availability of equipment and components, on the ambient electromagnetic environment, and on the topographical features of the installation area. At the lower frequencies (e.g., citizens band - 27 MHz) a large selection of circuitry and components is available. The free-space attenuation also tends to be low at these frequencies. The average noise power in urban areas increases at low frequencies, however, and may require higher transmitter powers. Efficient antennas tend to become large at low frequencies as well.

At higher frequencies (e.g., 1000 MHz and above) highly efficient directional antennas can be used to avoid interference between adjacent signposts. Urban noise tends to be much lower at these frequencies. These advantages are offset by the high atmospheric attenuation in these bands and the high cost and relative inefficiencies of components and circuits which operate at UHF and above.

3. Power. The method used for powering the signposts will have very significant effects on the overall system cost. A battery powered device will require periodic battery changes but will have a simple and dependable power supply subsystem and will be inexpensive to install. A device which requires an external supply will be more expensive to install, since tie in with the local power companies is necessary. This factor also puts constraints on where the devices may be mounted. The advantage for this approach is that maintenance and service expense is minimized.

4. Modulation. The principal function of the signpost is to transmit the signpost ID location in the form of a digital message. While any form of digital modulation could be used, binary noncoherent frequency shift keying (FSK) is most often used. This technique is easy to implement, has good error rejection characteristics, and can be used with threshold detectors to ensure that weak signals are ignored and only reliable messages based on strong signals are received.

5. Data Format. As a minimum, each message transmitted by the signpost must contain signpost ID and/or location. In addition the message may contain start and stop bits, synchronization codes, parity check bits, and error correction codes. The addition of ancillary data increases the reliability of transmission but at the cost of complexity and added expense.

6. False Alarm and False Dismissal. False alarm is the situation whereby a vehicle receiver recognizes noise or interference as a signpost signal when, in fact, the signal is not present. False dismissal is the

situation whereby a legitimate signal is present but is so weak in relation to noise and interference that the receiver does not detect it. A high threshold in a receiver will reduce false alarms but will also increase false dismissals. The threshold setting is a compromise which requires careful analysis of the transmission link characteristics. A reasonable (though arbitrary) requirement would be that, on the average, a vehicle should not encounter a message error more than once per month.

An example of a low-density signpost distribution is shown in Figure C-1. Signposts are placed at a density of approximately one signpost per square mile. The signposts are located at intersections of major thoroughfares in such a way as to maximize the probability that traffic through the area will pass signposts. While it is possible to traverse the area without passing at least one signpost, it would probably require numerous detours around major intersections. In general, a truck driving at random through the area on major streets would pass a signpost once every two miles. If the truck were making deliveries to side streets in the area, the maximum distance between signposts would be four or five miles.

The minimum required transmitted power for a signpost is a function of frequency, required receiver signal-to-noise ratio, range, and distance between signposts. For a simplified "first cut" analysis, the configuration shown in Figure C-2 can be assumed to represent the signpost arrangement.

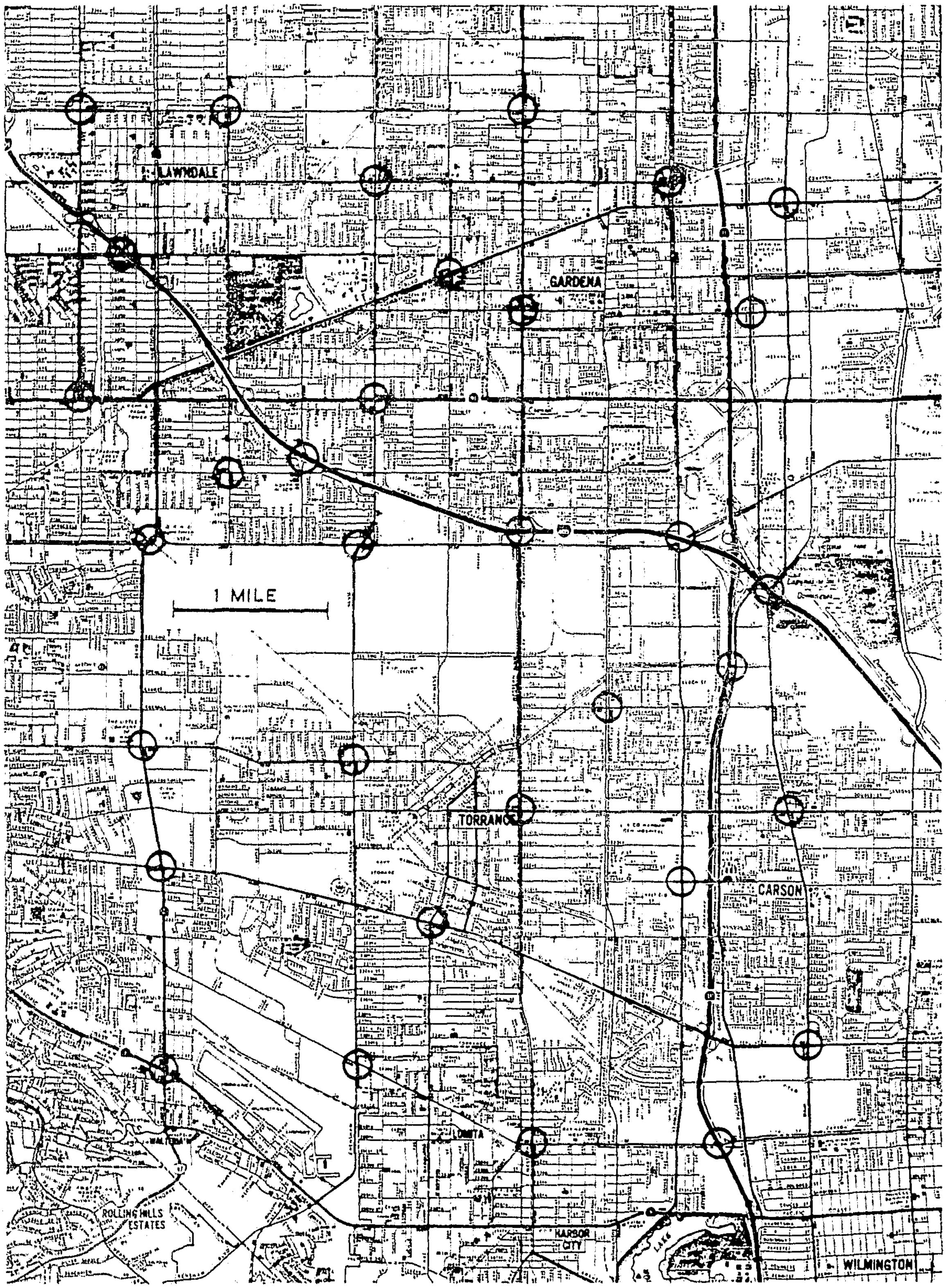


Figure C-1. Low-Density Signpost Distribution

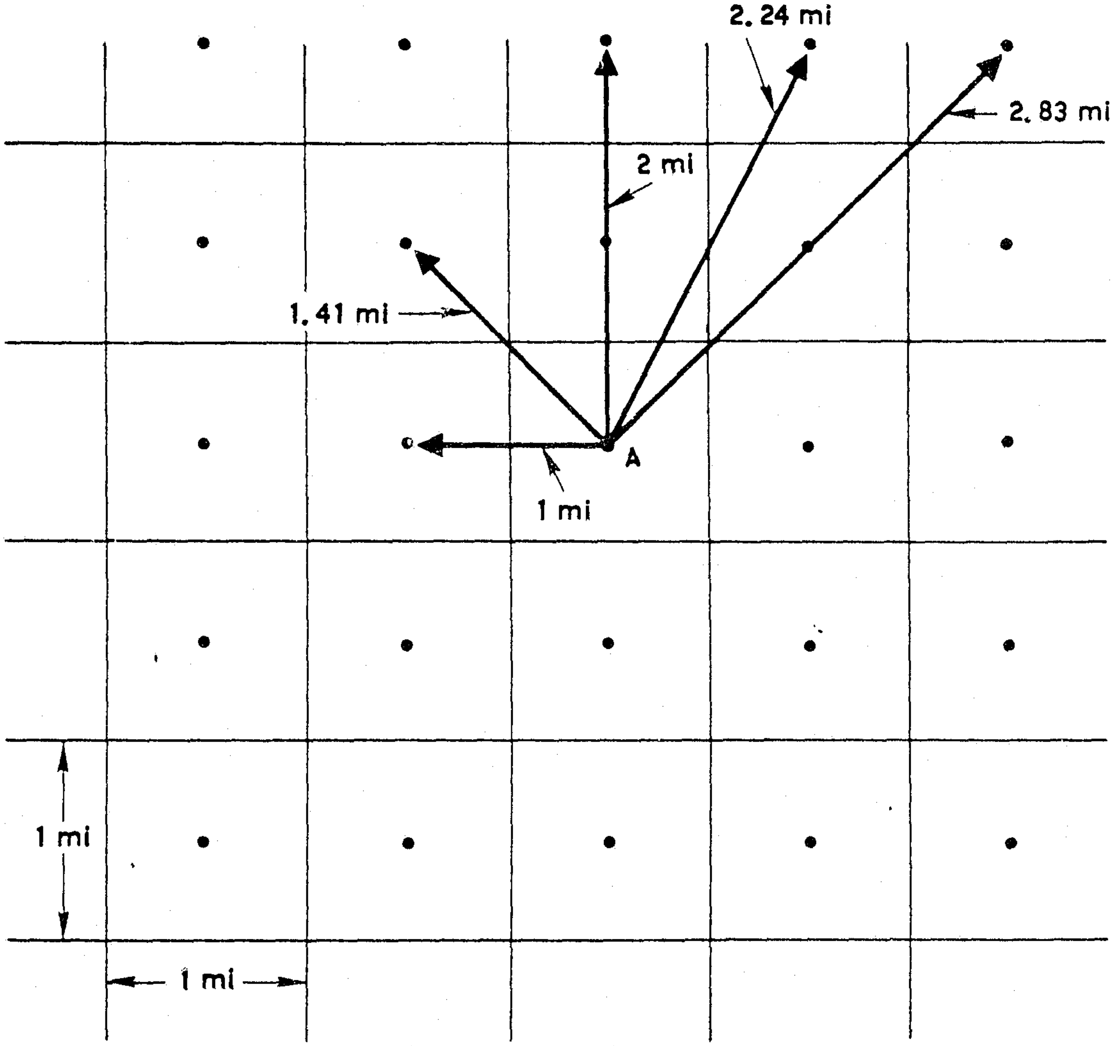


Figure C-2. Simplified Signpost Configuration

From signpost "A" there are four signposts at a distance of 1 mile, four at a distance of 1.4 miles, four at a distance of 2 miles, eight at a distance of 2.24 miles, four at a distance of 2.83 miles, etc. Each of these other signposts can be expected to contribute an interfering signal to a receiver in the vicinity of signpost "A." If the transmitter frequency is 150 MHz, the free-space path attenuation from these other signposts (assuming isotropic antennas) would be:

Distance (mi)	Attenuation
1.0	80 dB or 10^{-8}
1.41	84 dB or 4×10^{-9}
2.0	87 dB or 2×10^{-9}
2.24	88 dB or 1.67×10^{-9}
2.83	89.5 dB or 1.1×10^{-9}

if signposts at distances of 3 miles or more are ignored. If the receiver bandwidth is 10 kHz, the ambient noise level in an urban area at 150 MHz will be 2×10^{-10} milliwatts. The effective noise interference will be the sum of the ambient noise plus the interfering signals from nearby signposts. If the effective transmitted power from a signpost is P_t, the total interference in the vicinity of any particular signpost will be

$$2 \times 10^{-10} + (4 \times 10^{-8} + 4 \times 4 \times 10^{-9} + 4 \times 2 \times 10^{-9} + 8 \times 1.67 \times 10^{-9} + 4 \times 1.1 \times 10^{-9})\, P_t \text{ or } 2 \times 10^{-10} + (8.18 \times 10^{-8}\, P_t \text{ mW})$$

If signposts at distances of up to 5 miles are included the interference becomes

$$2 \times 10^{-10} + (11.58 \times 10^{-8})\, P_t$$

At distances of several miles in urban areas, the path attenuation values for free spaces conditions become unrealistic. The figures do illustrate some of the system design considerations however, and an overall interference function of

$$2 \times 10^{-10} + (12 \times 10^{-8})\, P_t$$

will be used as a reasonable approximation. This function is shown graphically in Figure C-3. The graph shows the total interference power increasing linearly with transmitter power when the signpost power is greater than -20 dBm. For power levels below -30 dBm, the ambient noise becomes the predominant factor.

The long dashed lines in Figure C-3 represent the received signal power (for an isotrophic antenna) at distances of 100 feet, 500 feet and 1500 feet from the signpost. At distances greater than about 1500 feet from the signpost, the signal is below the interference level. At a distance of 500 feet, the signal is generally about 10 dB above the interference level. At 100 feet, the signal is about 24 dB above the interference level. A detailed analysis of the communication performance of the short range link between the signpost transmitter and the vehicle will yield optimum threshold levels for the receiver to minimize false receptions. The short dashed line is indicative of a threshold 20 dB above the interference level. For this setting the vehicle would not accept signpost information until it came within approximately 200 feet of the transmitter.

It should be noted that, in the region of interest, the range of the system appears independent of the transmitter power (i. e., both the signal power and the interference power increase linearly with signpost transmitter power). In actuality, the receiver sensitivity will set a lower limit on transmitter power. For example, if the receiver sensitivity is -50 dBm and a 20 dB threshold is required, the transmitter power will have to be at least 0 dBm. The range of the transmitter will be about 200 feet and will not increase even if the transmitter power is increased.

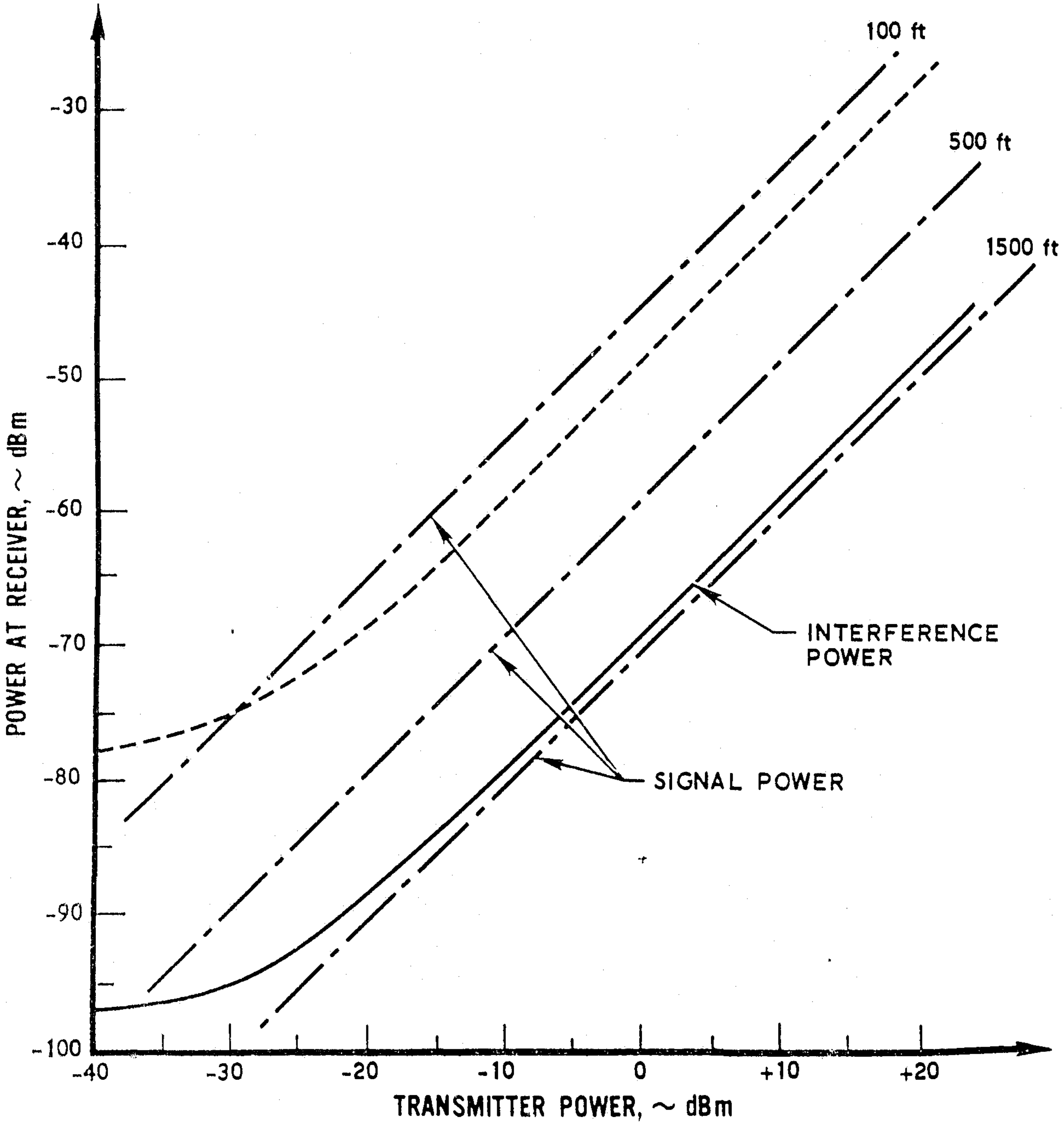


Figure C-3. Plot of Signal and Noise Power at Receiver as a Function of Transmitter Power

APPENDIX D. BATTERIES

1. Introduction

A battery to power an RF proximity unit has been investigated. In this system, the batteries would supply a 50-milliwatt load with a five-percent duty cycle and a five-year life. The system would be remotely located and would be subjected to a wide range of environments with humidities of 0 to 100 percent and temperatures from -50 to +165°F. Cost is an important factor in the selection of the system.

At the power levels specified, the energy requirement would be

$$\frac{50 \times 24 \times 365 \times 5}{1000 \times 20} \quad \frac{\mathrm{mW} \times \frac{\mathrm{hr}}{\mathrm{day}} \times \frac{\mathrm{day}}{\mathrm{yr}} \times \mathrm{yr}}{\mathrm{mW/W} \times \text{duty cycle}} = 109.5 \text{ Wh}$$

In a review of this application, the practicality of the Mallory solid-state battery and other low rate, long life reserve batteries were examined. A solar cell/secondary battery system was also studied.

2. Primary Batteries

A principal requirement for the primary battery is that it be free or nearly free from parasite losses. This requirement eliminates most common battery types such as the nickel-cadmium, lead-acid, and silver-zinc so it is necessary to examine those new classes of batteries developed for such items as heart pacemakers, electronic watches, and computer protection circuits. Three types of battery systems are considered. These are

(1) lithium-organic, (2) mercury-cadmium, and (3) the new solid state batteries. These are discussed separately in terms of the specified requirements.

a. Lithium-organic. A number of manufacturers have formulated lithium-organic cells based upon different cathode and electrolyte materials. These batteries have demonstrated good capacity down to -40°C and have no appreciable degradation after one year stand. These cells have high capacity loss above 120°F with about 13-percent loss of capacity in two months at 130°F and 20 percent loss at 160°F in the same time. The lithium-organic cells have good rate characteristics with a specific energy density of about 50 watt hours per pound and 3.7 watt hour/cubic inch in the "D" size. Operating voltage is about 2.5 volts per cell.

It would be expected that for high production quantities a battery cost of $60 to $100 would be involved. Some development cost and time, estimated at $20,000 and about four months, would be needed together with tooling costs.

b. Mercury-cadmium. The mercury-cadmium cell has better demonstrated charge retention characteristics than the lithium cell, especially under higher temperatures. The mercury-cadmium cell would meet the temperature range of -40°F to +160°F without any difficulty. A problem would be the lower energy density, about 15 watt hours/pound and slightly over one watt hour/cubic inch. Since the operating voltage is about 0.9 volts per cell, a higher number of cells in series would be needed to produce a typical operating voltage. Cost would be similar to that of the lithium-organic cells.

c. Solid state. The solid state battery is better than either the lithium-organic or the mercury-cadmium batteries for operation at the temperature extremes. Two types of solid state batteries have been developed: Gould has developed a silver-rubidium iodide cell which uses a $\mathrm{Rb\ AG_4I_5}$ solid electrolyte and Mallory has developed a lithium/heavy metal halide battery which has a doped lithium iodide solid electrolyte. The Mallory battery has an energy density of about 50 watt hours/pound and about 10 watt hours/cubic inch. The Gould battery has lower capability than the Mallory battery in terms of energy density with an energy density of 1 to 2.5 watt hours/cubic inch and about 100 watt hours/pound. Due to the high internal impedance the maximum current for current cells is limited to about 50 microamps so a number of paralleled cells would be needed.

It would be expected that cost of these batteries would be about the same as the lithium batteries.

A summary of various battery characteristics for "D" sized cells is given in Table D-1.

3. Solar Cell/Battery

As an alternative system it is suggested that the repeater system use a solar cell module/battery combination. Such systems are already in use for similar applications and would be cost competitive. In production quantities a plastic encapsulated solar cell module would cost under $70 per

Table D-1. "D" Size Primary and Secondary Batteries 1.3" O.D. × 2.3" Long (3 in.^{3})

Type	Leclanche	Nickel-Cadmium	Lithium-Organic	Solid Electrolyte	Mercury-Cadmium	Lead-Acid
Weight, lb	0.19	0.31	0.21	0.4 - 0.5	0.37	0.40
Capacity, AH	3.25	4.0	12.0	2.2 - 15	11.0	2.5
Relative Capacity						
R.T.	1.0	1.0	1.0	1.0	1.0	1.0
+160°F	0	0.40		1.0	1.0	
+140	0	0.60	1.0	1.0	1.0	1.0
-40	0	0.30	0.25 - 0.50	0.80	1.0	0.40
-65	0	0		0.85		0
Open Circuit Voltage	1.55 - 1.70	1.30	2.5 - 2.9	0.66/1.8	0.9	2.1
Watt hrs	4.0	5.0	30	2 - 25	68	5.2
Discharge Rate, amps	0.25	0.4	0.250	0.025	0.250	0.250
Operating Temp. Range, °F	0 - 120	-40 - 120			-40 - 160	-40 ~ 150
Capacity Loss/yr, %						
R.T.	12 - 18	100	0	0	0	70
+160°F	100	100	100	20	0	100
+140	100	100	60	15		100
-40	0	0	0	0	0	0
-65	0	0	0	0	0	0
Cost						
Per Battery, $	0.17	450	5.00	10 - 15	35	1.74
$/W hr	0.04	0.90	>0.50	>0.50	>0.50	0.33
Energy Density						
W hr/lb	21	16	154	5 - 58	25	13
W hr/in.^{3}	1.3	1.7	11	0.6 - 8.3	3.6	1.7

installation and a maintenance free lead-acid battery would cost about $10. With a charge regulator the entire system could be procured for under $100. The system would be sized so that the battery could sustain operation during nighttime and under adverse low solar incidence conditions while the solar cell module would have adequate capacity to provide battery recharge at the minimum solar incidence expected.

4. Conclusions/Recommendations

   a. The Mallory solid state battery is not immediately available for this application. Other battery systems might be more suitable. The cost of a battery system is anticipated to be about $75.00 per system.

   b. A solar cell/lead-acid battery system would be cost competitive with a primary battery system and could be immediately provided in test quantities.

APPENDIX E. DEAD RECKONING SYSTEMS

1. Conventional Dead Reckoning

The dead reckoning system is autonomous in that it employs equipment installed on the truck for determining location rather than depending on externally provided equipment. Examples of instruments used for dead reckoning are a magnetic compass and an odometer. This approach is differentiated from an alternative dead reckoning system, which transmits raw sensor data back to a base station where it is integrated and processed to obtain position fixes. This system has the advantage in that the base station processor makes use of city street maps to fit the vehicle path to the street pattern. Major drawbacks to this approach are the expense involved with having a sophisticated computer at the base station and the requirement for having a considerable amount of data transfer. In order to maintain a continuous track on a vehicle, sensor data should be relayed back to the base station at least once each four seconds. If each vehicle transmission required a 50-bit message to include a preamble, vehicle ID, and parity checks as well as the sensor data, there would be a contribution of about 12.5 bits per second from each truck. The average trucking company shares a mobile radio channel between 30 to 50 trucks. If all the trucks were using the location equipment the channel would have to handle 375 to 625 bits per second of data transfer. Requirements for message protocol or polling procedures would also increase channel usage.

This technique is suitable for situations where the user can dedicate a radio channel to carry digital data exclusively. The only users in this category are those who qualify for priority channel assignments by being in the military or public safety areas.

The candidate dead reckoning systems investigated in this report are as follows:

- Rate Gyro/Odometer
- Compass/Odometer
- Compass/Dual Odometer
- Compass/Rate Gyro/Odometer

All candidate systems employ instruments that provide information on the direction of travel (heading) and the distance traveled. The instruments provide an electrical readout which is fed to a simple computing circuit. This circuit computes the truck location in x-y coordinates. This information is then available for transmission to the central station at specific time intervals or on request.

a. Error sources. Typically, accuracy and cost are mutually opposing goals because more accurate equipment is usually more expensive. Judicious selection of components and system configuration can, however, frequently lead to optimum performance (i.e., least cost for the accuracy required). Thus the purpose of this study is to evaluate the potential accuracy of the candidate systems through an error analysis. The error analysis is conducted by first determining the influence of the component errors on the system location accuracy. The component error sources in turn form the basis for the study. These errors sources are discussed briefly in the following section.

(1) Magnetic compass errors. The major source of error in measuring the direction of travel is distortion of the magnetic field. The instrument errors due to the compass itself are typically small. The magnetic field of the earth contains local anomalies caused by various sources such as power plants and metal objects, like a passing car. These distortions are taken into account in the error analysis. Both the magnitude of the magnetic distortion and the correlation coefficient are considered.

The correlation is utilized to describe the relationship of field distortion between one point and another. Another source of compass error correlation can, for the most part, be adjusted.

(2) Odometer errors. The major error source in measuring distance traveled with an odometer is variation in tire conditions. Acceleration and braking cause relative motion between the tires and the road. Variations in tire pressure, speed, and the crown in the road also affect accuracy. The single largest source of error seems to be a slippery road condition, such as encountered during a rain storm. Errors contributed by the odometer itself appear to be quite small. An odometer distance measuring unit was installed and evaluated in the Aerospace feasibility demonstration system during FY 73. The characteristics and performance of this unit were considered satisfactory for use in an operational system as well as in the demonstration system. The odometer unit will utilize an electronic wheel actuator mechanically designed with standard SAE fittings so that it would interface with standard truck odometer drives. The wheel actuator will be

connected to an electronic counter to accumulate the pulses from the wheel actuator. Appropriate gear ratios and calibration procedures will be used to provide a ratio of one count per foot of truck motion.

Data from numerous test runs made by the demonstration vehicle were analyzed and statistical inferences were made. Repeatability of the odometer readings was found to be extremely good: results from a series of 18-mile runs yielded a standard deviation from the mean of 65 feet. These values represent less than 0.07-percent random error (one sigma). The systematic errors were found to be somewhat larger. The test runs revealed that the mean difference between odometer readings and measurements from the map used in the base station was 995 feet or 1.0 percent. It is probable that lane changes and freeway access roads, not accounted for on the map, were major contributors to the positive bias of the readings. This bias could be eliminated by marking the map with distance traveled figures obtained from actual measurements. The measurements would be made for specified route segments. The dispatcher would simply add the separate segments to determine the current vehicle position. The location within a particular segment would be determined using a planimeter directly with the map starting from the beginning of the segment. The use of low density signposts would also be effective in keeping systematic errors within bounds.

The only significant instrument consideration is quantization, i.e., the smallest measurable change in distance. Strictly speaking, there are both random and systematic error sources contributing to distance-traveled errors. The largest error source is the systematic error than can be modeled as an error in scale factor. A scale factor error contributes to location error that is proportional to distance traveled, while a random error only contributes an error that is proportional to the square root of distance. For simplicity in analysis, all the distance-traveled errors were lumped into the scale factor error. A conservative number of 0.3 percent was assumed for the standard deviation of this error.

(3) Rate gyro errors. A rate gyro provides a measurement of change in direction of travel rather than the actual direction of travel (heading angle) at an instant in time. The rate gyro measurements can be integrated (or summed at frequent but discrete time points) over a period of time. This integrated signal is the change in heading angle during the time period. The heading angle can then be computed by adding the computed heading angle change to the actual heading angle at the beginning of the time period. An estimate of the initial heading angle is used if the precise angle is not known.

The error model of an inexpensive rate gyro is complicated by the effects of nonlinearities. There are also errors in the scale factor and changes in the bias. Where possible, known error sources are assumed to be eliminated by compensation in the computation circuit. In this study all the residual error sources were lumped together and represented as a single random error source. This random error is assumed to contribute an error with a standard deviation of 0.08 degrees when integrated (or summed) over a period of 0.5 seconds. This value of 0.16 degrees per second is considered to be a conservative estimate of the errors that will be experienced.

(4) Dual odometer errors. A dual odometer operates by separately measuring the rotation of two wheels. The distance traveled is computed by averaging the two measurements. The change in heading angle is determined by differencing the two wheel measurements. The accuracy in the distance traveled can be expected to be the same as for a single odometer. Accordingly, for the standard deviation of the distance-traveled measurement error, a value of 0.3 percent is used in this study as discussed for the single odometer.

The error in the measurement of change in heading angle will depend on the difference in the tire conditions for the two wheels. Variations in the crown in the road, pressure of the tires, wind direction, truck load distribution and wheel slip will introduce errors. For this study, all the errors in measuring change in heading angle were lumped into a single random error source. It was assumed that the error in measuring the difference between the distances traveled of each wheel was 0.4 percent of the average distance traveled. Further, it was assumed that the errors were independent when sampled every 30 feet. Thus, when traveling at 40 miles per hour and sampling every one-half second (every 30 feet) the standard deviation of the error is 0.12 feet. This leads to a heading angle error of 1.5 degrees in 30 feet. i.e., 30.0 degrees per second when traveling 40 miles per hour.

(5) Computational errors. Current available computing circuits should be quite adequate so that computational errors will introduce

negligible effect on the location error. The speed of available circuits is also sufficient to permit the computation cycle to be short enough to overcome any possible sampling frequency difficulties, even at the fastest truck speed.

b. Summary of results. The basic configurations studied can be portioned into two generic groups. The configurations in the first group are as follows:

- Rate Gyro/Odometer
- Compass/Odometer

In these configurations there are only two measurements available, one heading angle or change in heading angle measurement and a distance-traveled measurement.

The rate gyro measures heading angle rate of change and, accordingly, exhibits a drift in computed heading angle. The rate gyro is, however, much more accurate than such other sensors as the dual odometer or a steering wheel sensor.

The magnetic compass differs from the rate gyro in that it measures the heading angle rather than change in heading angle. The magnetic compass does not exhibit the drift in heading angle as do the dual odometer and the rate gyro. Because of this drift characteristic the error analysis indicates that the compass/odometer system performs much better than the rate gyro/odometer system.

The configurations in the second group are as follows:

- Compass/Dual Odometer
- Compass/Rate Gyro/Odometer

In these configurations three measurements are available; i.e., heading angle, change in heading angle, and distance traveled. The two measurements concerned with heading angle must be combined to provide a single estimate of the angle. An algorithm for combining these measurements is established before the error analysis is conducted. The exhibit heading angle error depends on how the two measurements are combined. The distance-traveled error, on the other hand, will be the same for these configurations as for configurations of the other group. The error analysis indicates that the compass/rate gyro/odometer system is superior to the compass/dual odometer system simply because the rate gyro error is much less than the change-in-angle error, as measured by a dual odometer.

This summary of results is simplified by concentrating on the two strongest candidates; i.e., one from each of the two generic groups. In addition, the discussion is limited to a single route configuration. For this route the truck is traveling at 40 miles per hour in a straight line. The dead reckoning system does not use the fact that the route is fixed and the computing circuit updates the location estimate every 30 feet (every 0.5 seconds in this case). The straight line route is chosen because any other route selection will tend to decrease the location error for the same distance traveled. Also, at a fixed speed an error correlated in time is equivalent to an error correlated in distance (space). Thus at fixed speed and direction no distinction need be made between time and distance correlations.

(1) Compass/odometer system. The compass error model used for the error analysis was a two-parameter model. The two parameters are the standard deviation of the errors and the correlation coefficient. With standard deviation of error assumed to be 10 degrees, the compass measurement would exhibit errors in excess of 10 degrees over 35 percent of the time. If the correlation coefficient is assumed to be virtually zero, then the swings in the measurements would be very fast since the errors are independent in time.

For the case where the errors are uncorrelated, the contribution to the location error due to the compass errors can be computed from the following formula

$$\sigma_{xy} = \sigma_\theta \sqrt{S \cdot \Delta S} \qquad \text{(E-1)}$$

where

σ_{xy} = location error standard deviation

σ_θ = compass error standard deviation

S = distance traveled

ΔS = distance traveled per computation cycle

The location error for a system with an error-free odometer can be computed by using this formula. The location errors along the route are as follows:

Actual Distance Traveled (mi)	Location Error Standard Deviation (ft)
2	98
20	311
40	439

The contribution to the location error due to an odometer error with a standard deviation 0.3 percent are listed below:

Actual Distance Traveled (mi)	Location Error Standard Deviation (ft)
2	32
20	316
40	634

The total location error as a result of the error contributions from both the compass and the odometer can be obtained from these two tables.

The total location error is computed by combining the two error effects by using the root sum square method, which produces the following results:

Actual Distance Traveled (mi)	Total Location Error Standard Deviation (ft)
2	103
20	443
40	771

Thus, even with the conservative value for the error-source standard deviation, this candidate system offers excellent accuracy because the large swing in compass errors is averaged out.

The compass error can be expected to be correlated. Due to correlation, the speed of swing due to the errors is not as violent as without the correlation assumed for the previous computation. The true nature of the error correlation as experienced in an urban environment is not currently known. To show the influence of correlation, however, the previous computations will be repeated with a correlation coefficient of 0.7. The formula for location error can be modified to account for correlated errors as follows

$$\sigma_{xy} = \sigma_{\theta} \sqrt{S \cdot \Delta S} \left(\frac{1 + \rho}{1 - \rho} \right)^{1/2} \tag{E-2}$$

where ρ = compass error correlation coefficient and the other symbols are as in Eq. (E-1). Equation (E-2) is, in general, an approximation but is quite accurate in this particular case.

By using Eq. (E-2), the contribution to the location error due to the correlated compass error is as follows:

Actual Distance Traveled (mi)	Location Error Standard Deviation (ft)
2	233
20	740
40	1045

As before, the contribution to the location error due to odometer errors can be added using the root mean square method. The total location error, taking into account the combined effect of the two instruments, is as follows:

Actual Distance Traveled (mi)	Total Location Error Standard Deviation (ft)
2	235
20	804
40	1222

The correlation of compass errors obviously has a significant effect. The ultimate acceptability of this system seems to hinge on the specific type of compass errors that are exhibited in a urban environment.

(2) Compass/rate gyro/odometer system. The advantage of including a rate gyro in the dead reckoning system is that it provides the opportunity to decrease the heading angle error without significantly increasing the system cost. The compass measurement and the rate gyro measurement are combined in the computing circuit to provide an estimate of the current heading angle. As mentioned before, the magnitude of both the error in estimated heading angle and the error in location is affected by the choice of algorithm used to combine the compass and rate gyro measurements.

As a starting point a recursive, filtering algorithm was used. The equation for this algorithm is simply

$$\hat{\theta}_n = a\theta_n^* + (1-a)(\Delta\theta_n^* + \hat{\theta}_{n-1}) \qquad \text{(E-3)}$$

where

$\hat{\theta}_n$ = heading angle estimate at time t_n

$\hat{\theta}_{n-1}$ = heading angle estimate at time t_{n-1}

θ_n^* = compass measurement at time t_n

$\Delta\theta_n^*$ = rate gyro measurement integrated over time period t_{n-1} to t_n

a = filter gain

In using this algorithm the filter gain, a, was selected to minimize the error in estimated heading angle. For this criteria, it can be shown that the estimated heading angle error can be computed with the aid of the following equation.

$$\sigma_{\tilde{\theta}} = \sqrt{\sigma_\theta \sigma_{\Delta\theta}} \tag{E-4}$$

where

$\sigma_{\tilde{\theta}}$ = estimated heading angle error standard deviation

σ_θ = compass error standard deviation

$\sigma_{\Delta\theta}$ = rate gyro error standard deviation

This is, in general, an approximation but is quite accurate for this specific problem.

The addition of a rate gyro significantly reduces the estimated heading angle error. Starting with a compass error standard deviation of 10 degrees and then adding a 0.08-degree per cycle rate gyro to the system reduces the standard deviation of the heading angle error to 0.9 degrees.

The addition of the rate gyro increases the location long-term error because the resulting heading angle estimation errors are highly correlated. Note first that in the preceding calculations the compass errors are uncorrelated. Also the algorithm of Eq. (E-3) is optimal for minimum heading-angle error but it is not optimal for minimum location error. In effect, the magnitude of the location error is effected by magnitude of the sum of the heading errors, not the sum of the magnitude of the heading errors. It is this phenomenon that must be taken into account when improving performance.

The algorithm of Eq. (E-3) must be modified before the location errors for a system with the addition of a rate gyro can be properly evaluated. The study to date has shown that the addition of a rate gyro can provide improved accuracy when an alternate algorithm is used. However, the degree of improvement has not yet been determined. Note that so far the discussion has been limited to a compass with virtually uncorrelated measurement errors.

In the study to date, the problem of using a rate gyro to reduce the effects of correlation in compass errors has not been addressed. Another algorithm for combining compass and rate gyro measurements is required if the compass errors are significantly correlated. Although it may be that another simple recursive filtering algorithm will make an otherwise unacceptable system perform within tolerance, this cannot be determined with assurance until an error analysis is performed for that case.

(3) Simulation results. A simple computer program has been developed to simulate the error characteristics of the dead-reckoning system. A Monte Carlo simulation is employed to propagate the errors that would be encountered when a number of different trucks followed the same route. Sample results are shown in Figures E-1 through E-4. For this simulation the speed of each truck is 40 miles per hour. There are eight trucks following a straight-line route.

The distance-traveled errors for this sample run are zero. The compass heading errors are uncorrelated ($\rho = 0$) and standard deviation is 10 degrees (certainly a conservative number). The location errors along the route are as follows:

Actual Distance Traveled (mi)	Location Error Standard Deviation (ft)
2	124
20	210
40	447

The location error including an odometer distance errors of 0.3 percent can be readily added to the simulation results by the root sum square method. With the odometer errors included the total location errors are as follows:

Actual Distance Traveled (mi)	Total Location Error Standard Deviation (ft)
2	128
20	380
40	775

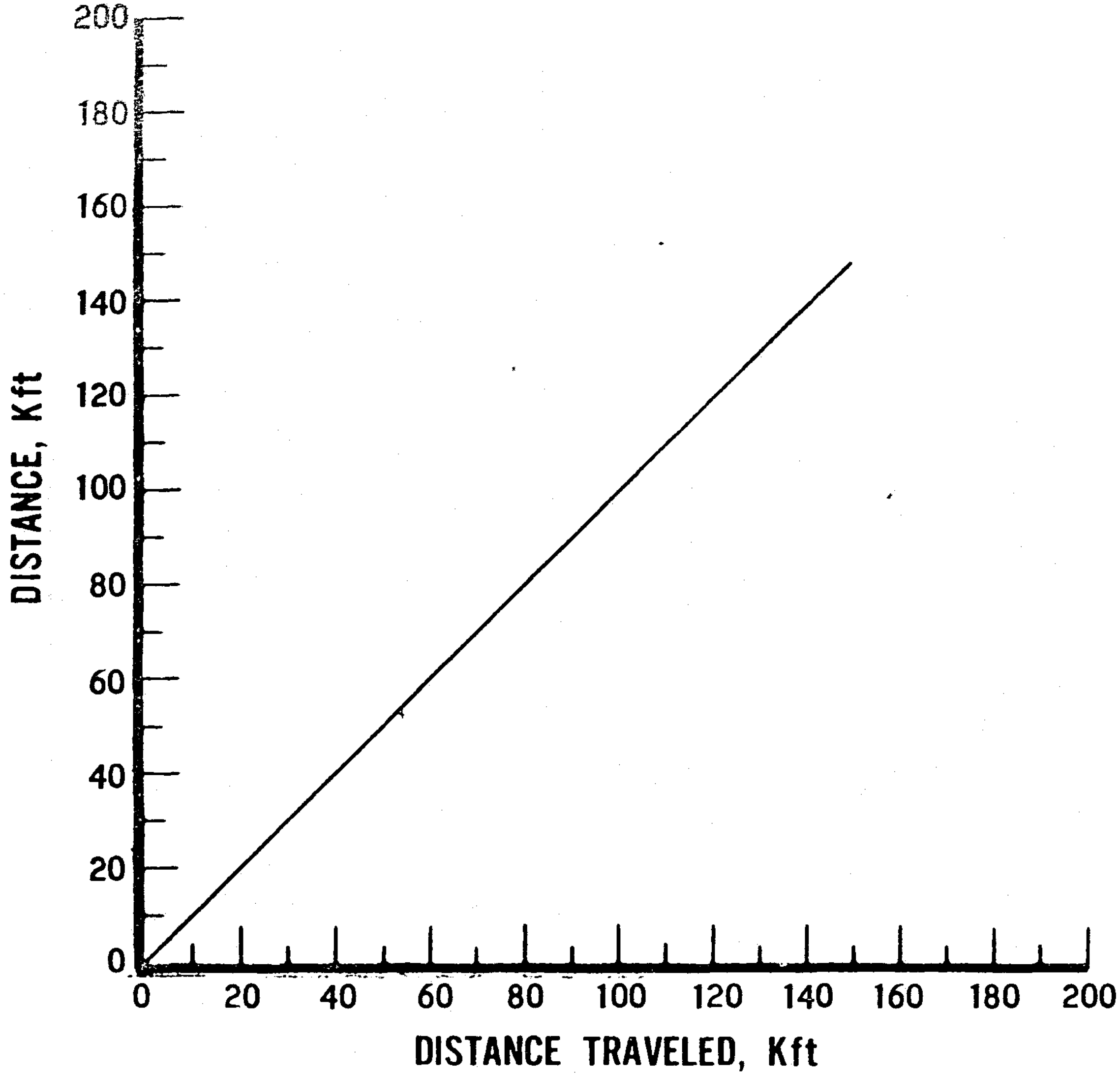


Figure E-1. Map of Truck Route Used for Simulation. Distance is measured in feet (40 miles total) and the truck speed is 40 mph.

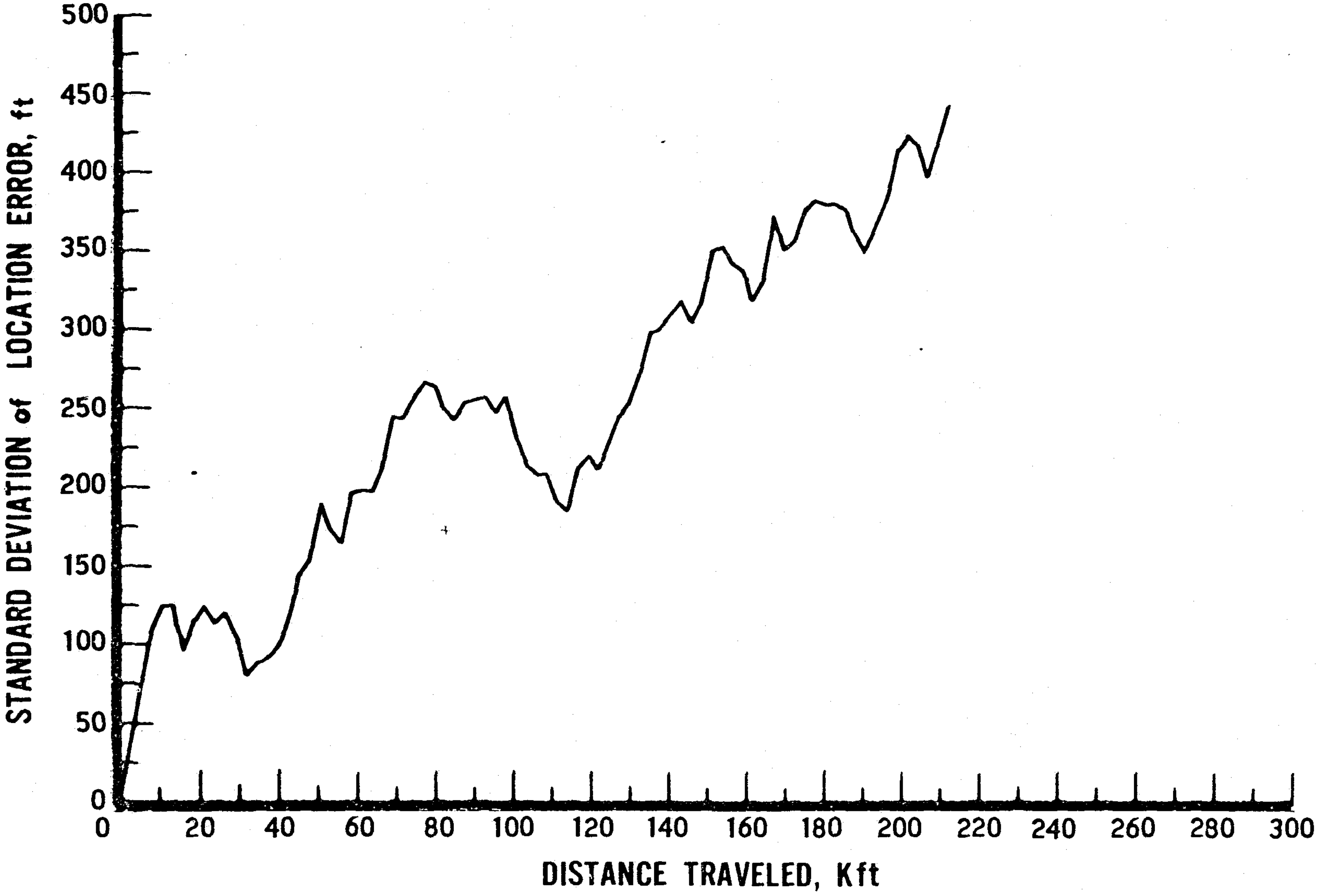


Figure E-2. Standard Deviation of Location Error as a Function of Distance. Standard deviation and distance traveled are both indicated in feet. Standard deviation is computed through root sum square of the location errors of each truck.

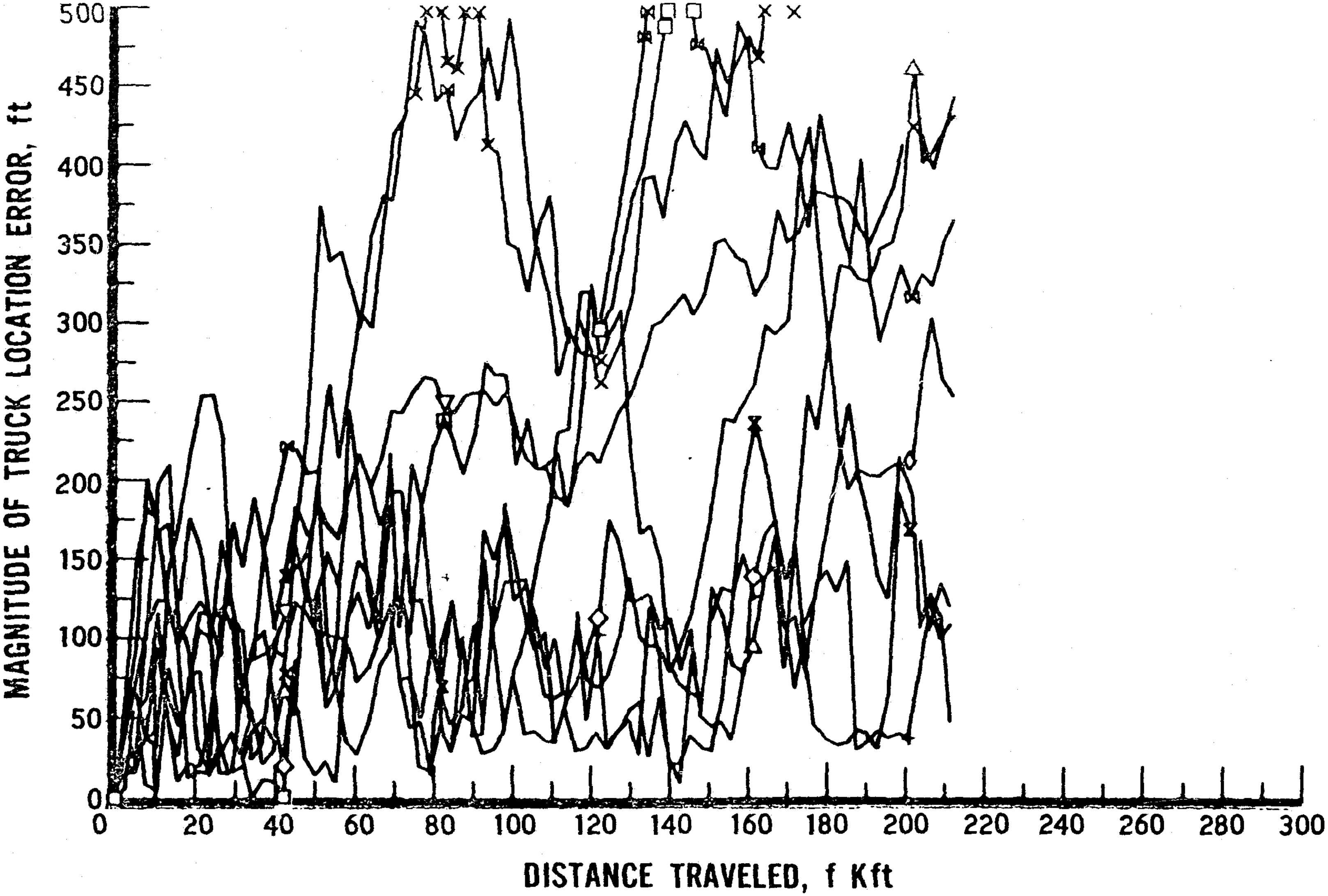


Figure E-3. Magnitude of Truck Location Errors as of Function of Distance. Magnitude of error and distance are in feet. Each curve traces the magnitude of the location error for a truck as a function of distance traveled.

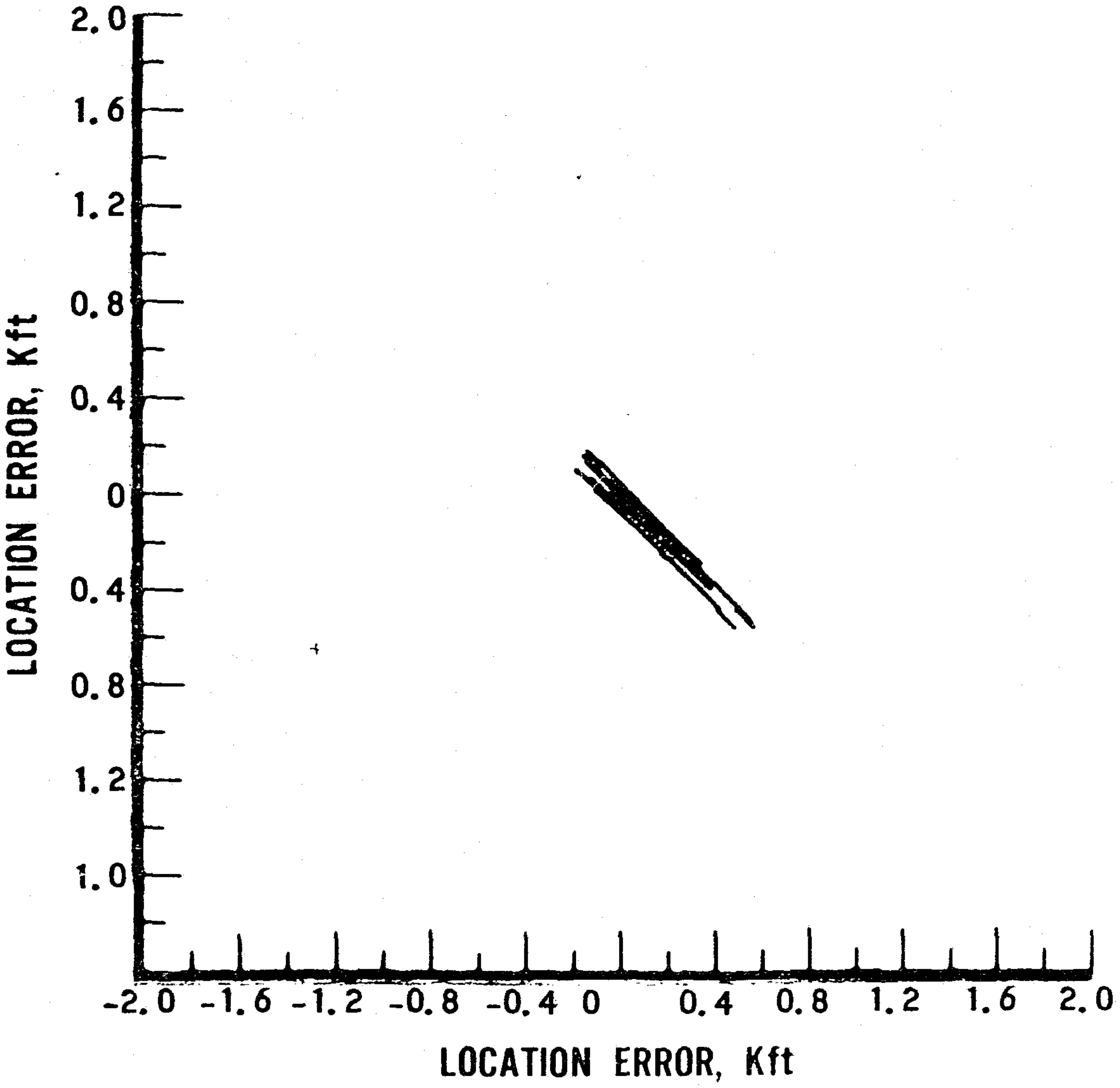


Figure E-4. Components of Truck Location Errors. The X and Y components of the location error for each truck (measured in feet) are traced and superimposed on this one composite plot.

The sample results shown in Figure E-2 are not in precise agreement with the analysis because this simulation utilizes only eight trucks. A simulation employing many more trucks would conform more precisely to the analytical results. Simulation results do confirm that the systems studied are feasible provided the error sources, as modeled, are correct.

2. Hybrid Dead Reckoning

Hybrid dead reckoning refers to truck location using instruments contained within the truck supplemented by occasional calibration of the instruments using support elements (signposts), wayside transmitters or similar units which provide the vehicle with absolute position information deployed in a low density configuration. The basic instruments under consideration are an odometer, a compass, and a rate gyro in conjunction with support elements.

The cost of implementing a hybrid dead reckoning system is potentially low with respect to the truckborne instrumentation, and the overall cost is dependent upon the net signpost cost. The latter cost is related to the accuracy of dead reckoning; i.e., truck location accuracy between signpost updates. High accuracy of dead reckoning implies low signpost density and lower signpost cost.

An analysis was performed to develop a relationship between maximum signpost separation and the relevant error parameters. This relationship is as follows:

$$S \leq \frac{\sigma_T^{\,2}}{2\sigma_\theta^2 S_c}$$

where S is the maximum signpost separation, σ_T is the allowable standard deviation of the location error, σ_θ is the standard deviation of the heading error and S_c is the correlation distance constant for the heading sensor.

The maximum signpost separation is shown in Figure E-5 as a function of compass error for several values of compass error correlation distance. In each case the allowable standard deviation of the location error is held to 300 feet. The figure indicates that if the compass error was 6 degrees and if the error correlation distance was 100 feet, a truck would have to pass a signpost at least once every eight miles in order to keep the location error within 300 feet.

The computer simulation (as described) was performing using a compass error of 10 degrees. This simulation indicated that a 300-foot location error could be maintained with a signpost separation of up to 15 miles. This result was due to the fact that the simulation assumed an uncorrelated compass error.

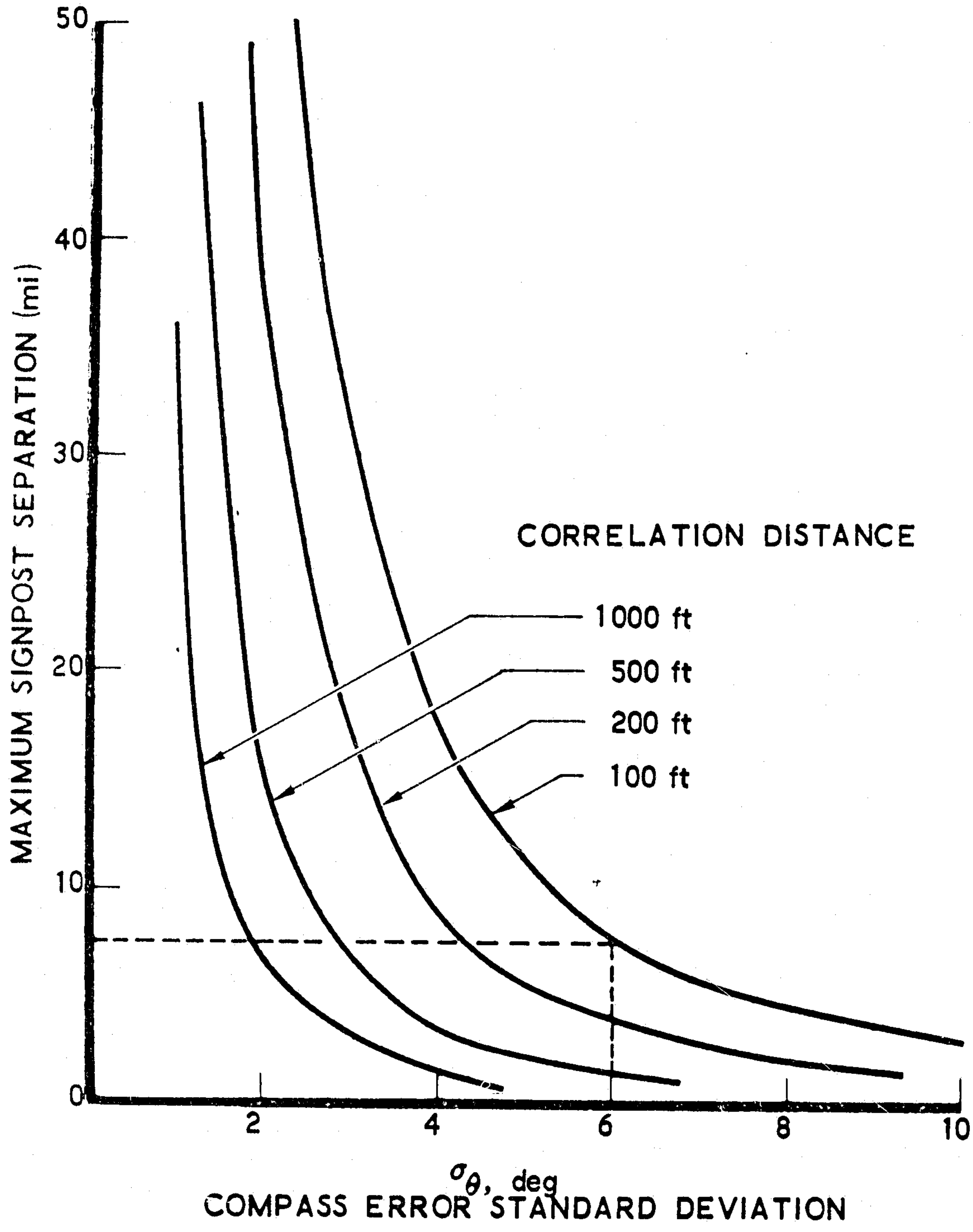


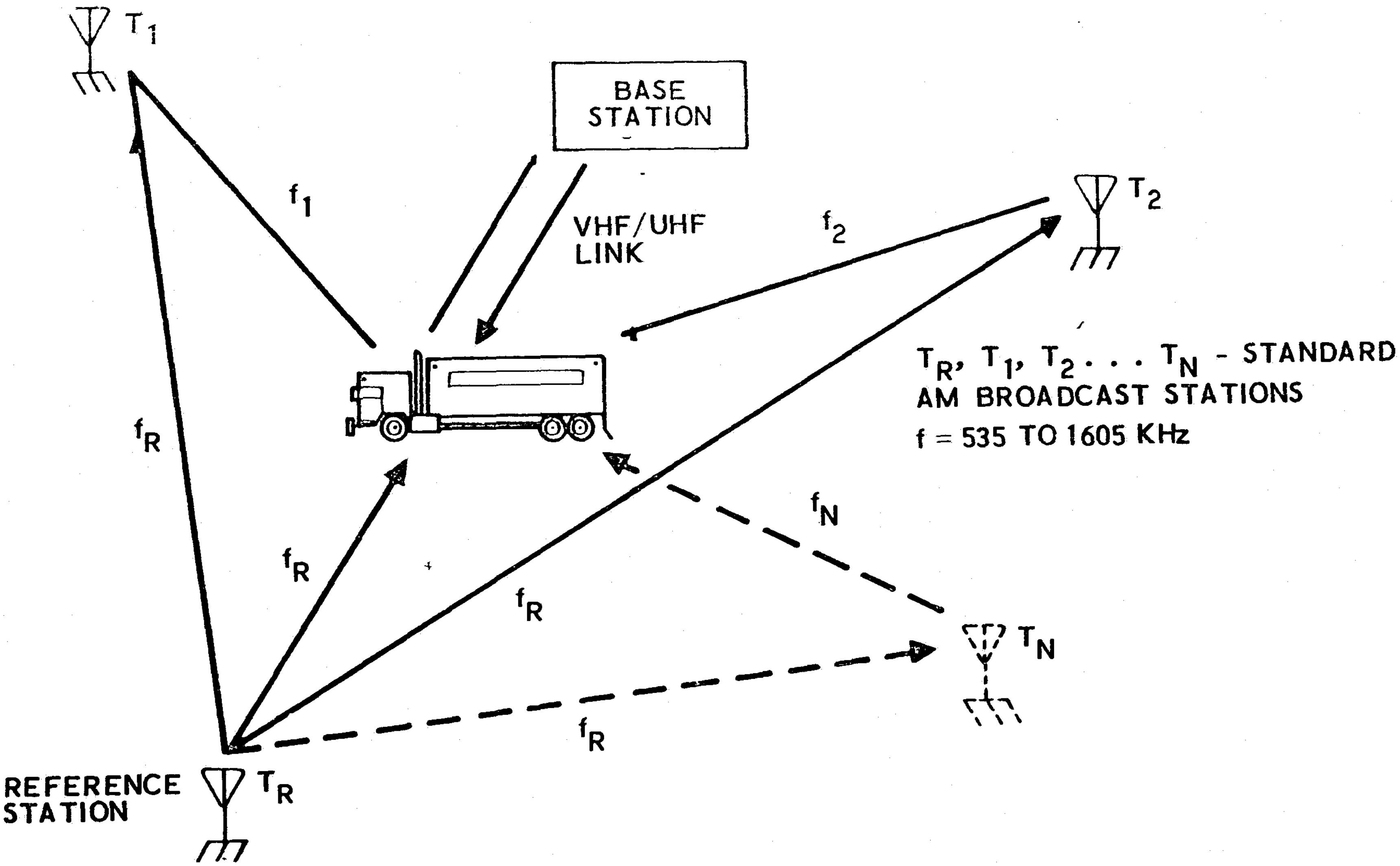
Figure E-5. Maximum Support Separation for 300-Foot Location Error

APPENDIX F. AM PHASE-LOCK HYPERBOLIC SYSTEM

This appendix defines a concept for vehicle location based on measurements taken on local AM radio broadcast station signals. The basic objective is to locate a vehicle by measuring the range difference between the vehicle and three or more local AM broadcasting stations, as shown in Figure F-1. To establish a stable hyperbolic pattern, one selected AM station will have its transmitter carrier frequency stabilized using an atomic standard and the other stations will have their carriers phase-locked to the standard. The atomic standard would be a commercial instrument costing between $6, 000 and $8, 000 and having a stability of one part in 10^{10} or 10^{11} per day. Since each of the AM stations are, in principle, absolutely stable in frequency, one can measure the range difference between these AM stations and directly determine present vehicle position relative to some initial starting position.

1. System Definition

The principal error source which must be evaluated and dealt with is that resulting from propagation anomalies. These anomalies include such problems as multipath signal summation and direct path attenuation caused by buildings and topography. There does not appear to be quantitative information as to the order of magnitude of these errors at AM broadcast frequencies (535 to 1600kHz). There are data at VHF and UHF frequencies which indicate that typical RF energy ensemble delays in large cities are occasionally on the order of three microseconds but can sometimes be as large as 15 to 20 microseconds. If this were also true at broadcast frequencies, it would



T_R, T_1, T_2 . . . T_N - STANDARD AM BROADCAST STATIONS

f = 535 TO 1605 KHz

Figure F-1. AM Phase-Lock Location System imply errors on the order of 3,000 feet or more. On the other hand, there is evidence that there is not as much "echoing" at broadcast frequencies as at VHF and UHF; therefore, resultant errors could be much less than 3,000 feet. By choosing three (or more) broadcast stations at diverse locations, one can also have the advantage of space diversity as well as frequency diversity, and this could significantly reduce errors due to propagation problems. This problem remains to be investigated more thoroughly.

There are various ways in which one can configure the proposed system. Figure F-2 is one embodiment*. Basically, three simple AM receiver channels are always tuned to three different AM broadcast station frequencies. The output of each AM receiver is sent to narrow-band, phase-lock loops (PLL) which, in effect, strips away the audio side bands and locks on to the main RF carrier. In addition, the phase-lock loops are locked in such a manner as to yield a clean output signal at 10 times the input frequency.† This permits simple measurements of time differences at one-tenth the interval of one RF carrier cycle. One of the three AM receivers is arbitrarily called the <u>reference channel</u>. This channel is similar to the other two except that the phase-lock loop is set to divide by factor on the order of 100. The output of the reference

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*The frequencies and scale factors shown in Figure F-2 are illustrative only and subject to optimization.

†It is important to note that the PLL is operated very narrow band and thereby provides a memory (coast) function to eliminate momentary signal excursions and fade problems.

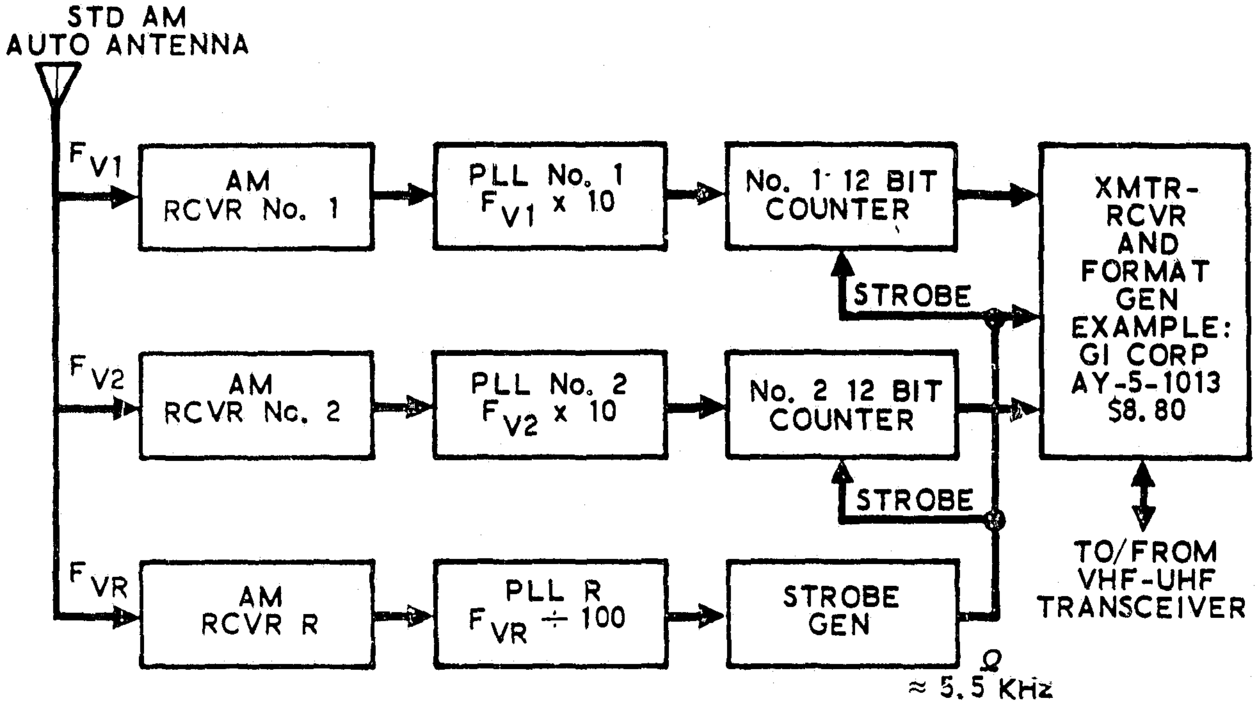

Figure F-2. AM Phase Lock Locator Block Diagram
(Base Referenced Vehicle Locator)

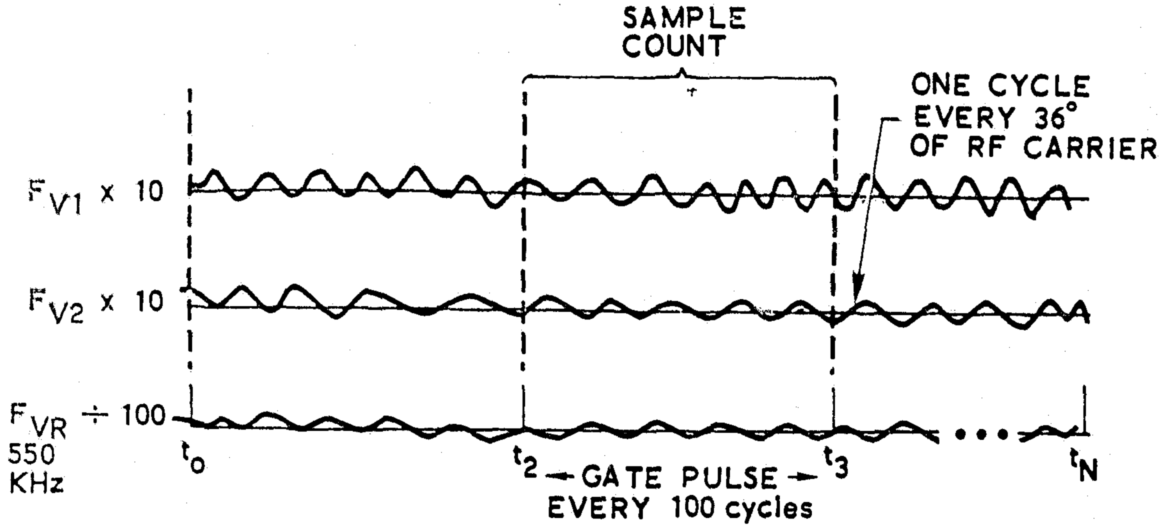

Figure F-3. Timing Diagram AM Phase-Lock Locator channel PLL triggers a sharp strobe generator which periodically reads the value of a first and second counter. These counters are driven by the first and second PLLs as noted in Figure F-2. Figure F-3 shows typical timing diagrams.

Note that counters No. 1 and No. 2 are operated in module N mode and only the least significant characters are retained; N is a function of maximum resolution and operating radius desired. For a 40-kilometer radius from base station and 20-meter resolutions, N is 2000. A 12-bit counter including parity is suggested. Once initialized at a known location relative to base station, counters No. 1 and No. 2 never stop but are read out (strobed) at a specific point in time, t_N, defined by the reference AM station; these points (t_N) are in synchronization with base station readings.

The system measures the change in path length between a first AM broadcast station to the vehicle, and the reference AM broadcast system to the vehicle. This gives a first hyperbolic line of position. Secondly, the system measures the difference between a second AM station, the vehicle, and the reference AM station. This gives a second hyperbolic line of position. This process results in a unique vehicle location plus one ambiguity. The ambiguity can be easily eliminated because of prior knowledge of vehicle position. Computationally, this concept is similar to LORAN and other hyperbolic position determining systems.

A possible operating procedure is as follows. The system in the vehicle is initialized to some known location by first inserting the correct number into the counters then immediately connecting the counters to their PLL.

As the vehicle moves, or due to instabilities, these counters will change. The base station polls each vehicle periodically via the existing VHF/UHF transceiver in the vehicle to determine automatically the reading of each counter, vehicle address, and other pertinent information. The base station receives the reply via the vehicle transceiver. A message of about 36 to 48 bits in length will probably be adequate per reply. The entire inquiry/reply could be done in about 15 to 20 milliseconds.

The actual vehicle-locating operation would be done manually using a simple graphical procedure or a small computer could be interfaced directly with the communications link to automatically calculate the locations.

The practicality of the proposed system will depend a great deal on the equipment simplicity and cost, as well as on accuracy. In this connection it is worth noting that almost all of the component parts of the proposed system are available today in low cost integrated circuit modules. For instance, relatively sophisticated precision phase lock loops and binary counters much longer than needed are available for under $5 each. The proposed system comprises parallel channels which are essentially identical. A realistic design goal is to have each channel cost under $50. The cost of the complete vehicle-mounted equipment should be less than $300, excluding the communications transceivers. The system's AM receivers can probably be simple narrow-band, integrated-circuit RF amplifiers or another phase-lock loop. It is not advisable to use a superheterodyne receiver since in this case one would separately have to take account of frequency instabilities in the local oscillator. The entire system would be packaged on a card.

2. System Errors

As long as each of the vehicle phase-lock loops remains locked to its respective AM carrier signals, the counters will provide valid information from which the vehicle position may be calculated. Multipath effects on one or more of the signals will occasionally cause position errors to appear; however, these errors will be relatively small and will be bounded. Should any of the loops lose lock, very large errors will be generated and these errors will not be subsequently corrected except by some form of re-initialization.

The cause of a phase-lock loop losing lock or slipping cycles is due to the presence of noise along with the input signal. In general, a signal-to-noise ratio of +6 dB is needed for the loop to acquire the signal. If modulation or transient phase error is present, a higher signal-to-noise ratio is needed to acquire and hold lock. The signal-to-noise ratio is related to the loop noise bandwidth. This bandwidth is subject to two conflicting requirements:

- The loop bandwidth must be narrow to minimize the external noise which enters the loop
- The loop bandwidth must be wide to enable the loop to quickly acquire and track the signal

To illustrate several of the loop design considerations, some preliminary estimates can be made of expected performance. If a carrier signal of 1 MHz is assumed, frequency variations due to transmitter instability should be no greater than about 0.1 Hz. Similarly, doppler shifts due to vehicle motion should be less than 0.1 Hz. Frequency variations due to multipath are unknown; however, a reasonable estimate for a loop which could track the signal under all expected conditions would have a natural frequency of 10 Hz. If this figure is used as a first estimate and if a critically dampened loop filter is assumed, a loop noise bandwidth of approximately 40 Hz would result.

The average noise power expected in a 40 Hz band at 1 MHz is approximately -110 dBM. The average signal power received from a 1 MHz, 50 kW transmitter at a distance of 100 miles is about -64 dBM. Of this power, approximately one-half, or -67 dBM is carrier (assuming 100-percent modulation). If the remaining -67 dBM were uniformly distributed as sideband energy over a 10 KHz bandwidth, approximately -94 dBM will appear as interference in the 40 Hz bandwidth of the loop. If a receiver noise figure for the front end is 7 dB (antenna, cable, preselect filter, etc.); the noise at the loop input will be -110 + 7 = -103 dBM. The total noise plus interference at the loop input will be -93.5 dBM and the overall carrier-to-interference ratio at the loop input will be +26.5 dB.

Analysis[10] has shown that a signal-to-noise ratio of 10 dB would result in a mean time to unlock of 10^6 seconds for a first order loop with a 40 Hz bandwidth. This would be equivalent to less than one cycle slip per day in continuous operation. Operation at signal-to-noise levels greater than 20 dB would make cycle slipping highly unlikely except in cases where the truck spent long periods of time in tunnels or other enclosed, well-shielded areas. For these cases, proximity units could be positioned at key locations to automatically provide re-initialization to the counters. The signposts could also be located at terminals and other areas frequently passed by vehicles.

APPENDIX G. POLICE RESPONSE MODEL

The police response model which follows was developed to identify system parameters which affect the ability of security forces to respond to a hijacking. In the initial stages of this development it is necessary to model the system in a general manner which does not utilize specific hardware parameters for a particular anti-hijacking system. It is more desirable, for design purposes, to evaluate system parameters which are functions of hardware design than to limit the investigation to a particular design concept. Thus, police response time is being modeled as a function of system parameters which themselves might be considered as functions of a wide range of hardware design parameters. The first section of this appendix sets the strategy to be followed in developing the model and it outlines the scenarios to be investigated. The mathematical model development and the results of parameter studies using this model follow in subsequent sections. Conclusions and recommendations based on the parameter studies constitute the final section.

1. The Response Problem

The general problem of defining a police response model to a hijacking is complicated by the limitless combinations of hijacking and response scenarios which might be envisioned. Questions such as (1) Do the police know where the hijacked truck is, (2) How accurately is the truck's position known, and (3) What type of pursuit method is employed by the police immediately bring many hijack-response scenarios to mind. For this reason, the philosophy taken in this study is to bound the scenarios with best and worst case response examples whenever possible. In this way, distinctions between the various choices can be more clearly delineated and scenarios lying between the two extremes can be bounded.

In responding to a hijack alarm, the most immediate question of importance to the police is the truck's location. Here, two extreme situations suggest themselves immediately: (1) the truck's position is unknown within the police patrol area, and (2) the truck's position is known at all times. The first situation suggests a random search by the police and this case will be studied in Section 3. The second possibility suggests further questions concerning the truck's movements and the police pursuit scheme.

The time taken to commit a hijacking will be considered as the sum of three times, these being the time to break in (t_B), the time to transport the truck (t_T), and the time to unload the cargo (t_U). The truck is moving only during the transport time, so the hijack scenarios which suggest themselves, depending on whether one or more of these three is zero, are as follows:

(i) The truck remains stationary during the break in (t_B), runs to a transfer point (t_T), and is stationary during the unloading (t_U).

(ii) The truck runs to a transfer point (t_T), and is stationary during the unloading (t_U). $\left[t_B = 0\right]$

(iii) The truck remains stationary during the break in (t_B), and runs to an undetectable terminal (t_T). $\left[t_U = 0\right]$

(iv) The truck remains stationary throughout the hijacking ($t_B + t_U$). $\left[t_T = 0\right]$

(v) The truck runs to an undetectable terminal (t_T). $\left[t_U = 0\right]$

The possible police response scenarios are almost limitless depending upon the number of police vehicles involved, the pursuit algorithm used by the police, how accurately the truck's position is known, the terrain, the type of police vehicle employed, and the type of detection equipment available to the police. When the various response models developed from these considerations are applied to the hijack scenarios suggested above, it is clear that the possible hijack/response scenario combinations are too numerous to handle in this preliminary study. Therefore, liberal and conservative pursuit algorithm is optimistic from the point of view that it takes advantage of the best possible circumstances for a police response, whereas the conservative algorithm attempts to pessimistically bound the police response time by assuming a worst case police pursuit scheme. The pursuit models are as follows:

A. Liberal pursuit. From N police vehicles in the patrol area, the vehicle which can respond to a given fixed point in the least time is chosen. This model assumes that the truck is stationary or that an intercept point is known precisely for each of the N patrol vehicles.

B. Conservative pursuit. From N police vehicles in the patrol area, the vehicle which can respond to a given fixed point of the hijacking, follow the hijacked truck along its transport route, and search an area of uncertainty around the truck in the least time is chosen.

The latter pursuit method is conservative for several reasons. First the path which the pursuing vehicle follows is not the most direct one between its initial point and the eventual point of detection (i.e., the point where the police vehicle finds the truck). The liberal pursuit, for example, takes the police vehicle directly to the point of detection. Other pursuit paths which might assume periodic updates on the predicted intercept point lie somewhere between the extremes of pursuits A and B. Secondly, the use of one vehicle throughout the pursuit is more conservative than using two or more vehicles in a cooperative pursuit/search scheme. The selection of the vehicle which responds in the least time from a group of N is not the most conservative approach, but it is realistic. The vehicle which can respond fastest to the original alarm point (i.e., the closest one to that point) will perform the entire pursuit in the least time, since the pursuit time is directly proportional to this fixed point response time. It is not unreasonable to assume that the vehicle closest to the original alarm point will be chosen because this is done routinely now.

The other questions which were raised about how to formulate the police response model, which concerned the number of police involved, the accuracy of the truck's position, the terrain, and the police equipment, will be addressed as the model is developed. Many of these unknowns will either be model parameters or closely related to these parameters. Of the ten combinations of hijack/pursuit scenarios which might be chosen, the two which bound the others are the combinations (pursuit A, hijack iv) and (pursuit B, hijack v). The combination A - (iv) represents the most optimistic police response situation since pursuit to a fixed point is required. Combination B - (v), however, couples the slowest pursuit algorithm with the hijack scenario which is most difficult to detect. Hijack (v) is the most difficult to detect because the truck is constantly moving. The truck speed reduces the police vehicle's effective pursuit speed which is the speed of the police vehicle relative to the truck. In the pursuit model results displayed in Section 6., these two pursuit/hijack scenarios will be emphasized.

2. The Police Service Queue

In both the random search and pursuit/search models which are developed in later sections the police availability probabilities are used. These probabilities are found with the help of statistical queuing theory. The individual probabilities that k calls (k = 1), . . . , ∞) are being serviced or are awaiting service are denoted by p_k (k = 1, . . . , ∞). The evaluation of these probabilities proceeds as follows.

Let N be the total number of police vehicles in the service pool (or in a patrolled area). If the service time t for the queue is exponentially distributed, with average service time t_s, i.e.

$$\text{prob}\ (t > \tau) = e^{\frac{-\tau}{t_s}}, \qquad (1)$$

and the call arrivals are Poisson in nature[11] with the probability of an arrival in time interval Δ given by $\lambda\Delta$, then statistical equilibrium on the probability p_k between times t and t + Δt demands

$$p_k\ (t + \Delta) = p_k\ (t) \left[1 - \lambda\Delta - k\frac{\Delta}{t_s}\right] + p_{k-1}\ (t) \left[\lambda\Delta\right] + p_{k+1}\ (t) \left[(k + 1)\frac{\Delta}{t_s}\right];\ (k < N) \qquad (2)$$

$$p_k\ (t+\Delta) = p_k\ (t)\left[1 - \lambda\Delta - \frac{N\Delta}{t_s}\right] + p_{k-1}\ (t)\left[\lambda\Delta\right] + p_{k+1}\ (t)\left[\frac{N\Delta}{t_s}\right];\ (k \quad N) \quad (3)$$

In Eq. (2), $\lambda\Delta$ represents the probability of a call arrival in time Δ, and $j\,\frac{\Delta}{t_s}$ represents the probability of a call being serviced and completed in time Δ, where Δ is assumed small. The actual probability of one call out of j being completed in time Δ is given by $j\left[1 - \exp\left|{}^{-\Delta}/t_s\right|\right]$. Thus, for small Δ this becomes $j\ {}^{\Delta}/t_s$. If one were to divide Equations (2) and (3) by Δ and find the limit as $\Delta \longrightarrow 0$, differential equations in p_k would result. It can be shown(12) that such equations have a steady state limit, and it is this steady state behavior of the queue in which we are interested. Under the steady state assumption that $p_k\ (t) \longrightarrow p_k$ when $t \longrightarrow \infty$ the finite difference equations for p_k become

$$0 = -p_k\left[\lambda + \frac{k}{t_s}\right] + p_{k-1}\left[\lambda\right] + p_{k+1}\left[\frac{k+1}{t_s}\right];\ (k < N), \qquad (4)$$

$$0 = -p_k\left[\lambda + \frac{N}{t_s}\right] + p_{k-1}\left[\lambda\right] + p_{k+1}\left[\frac{N}{t_s}\right];\ (k \geq N). \qquad (5)$$

The solution to this set of equations is

$$p_k = \begin{cases} \dfrac{(N\rho)^k}{k\,!}\ p_o & ; \quad (1 \leq k \leq N) \qquad (6) \\[2em] \dfrac{(N\rho)^k}{(N!\ N^{k-N}}\ p_o & ; \quad (k > N) \quad , \qquad (7) \end{cases}$$

where $\rho = \frac{\lambda ts}{N}$, and p_o is chosen to satisfy $\sum\limits_{i=o}^{\infty} p_i = 1$.

Thus using Eqs. (6) and (7) and this summation to solve for p_o yields

$$p_o = \left[\sum_{i=0}^{N-1} \frac{(N\rho)^i}{i!} + \frac{1}{1-\rho} \frac{(N\rho)^N}{N!} \right]^{-1} \tag{8}$$

The parameter ρ may be thought of as the average fraction of time each patrol vehicle spends in servicing calls, and is known as the one vehicle utilization for the system.

3. The Random Search Model

One of the scenarios outlined in Section 1 was that in which the police must find a hijacked truck with little or no information regarding its position (i.e., without the aid of a hijack monitor and alarm system). It will be assumed that the search is centered around a known point where the truck was last seen or where it was expected to be at some earlier time. The basic assumptions which will be used are as follows:

- The vehicles used in the search are drawn from a fixed population of police vehicles which normally patrol a fixed area, and vehicles from neighboring areas do not participate.
- The terrain is that of a large city and a methodical search requires a rectangular search pattern which generally is conducted along streets in the city. This assumption although necessary for a land vehicle police unit does not preclude the use of helicopters since city buildings might obscure a truck from sight unless such a search pattern is adopted.

- The truck is considered found if the area searched by the police is greater than or equal to the possible area in which the truck could be located. This is a very optimistic assumption since the truck may appear in areas searched by the police at a former time. It is felt, however, that this optimism does not overly weigh the chances of detection in favor of the police, as the results will show.
- The time needed for police vehicles to assemble at a starting point and to transfer from one search sector to another is considered negligibly small in comparison with the total search time.

Under these assumptions, the probability of the truck being detected in time t is pd(t), where pd(t) consists of a probability of being detected by vehicles actively searching and a probability of being detected by other patrol vehicles.

$$pd(t) = \hat{p}_{N_p} \left\{ \frac{v_S d_S t}{\left[\frac{4(t_D + t)^2 v_T^2}{N_p} \right]} \right\} + \frac{(N - N_p)\, d_S^2}{\max\left| D^2, 4(t_D + t)^2 v_T^2 \right|} \tag{9}$$

$$\hat{p}_{N_p} = \sum_{i=o}^{N-N_p} p_i \quad , \tag{10}$$

Equation (10) represents the probability that $(N-N_p)$ or fewer calls are in the police queue or that N_p cars are free to respond to a call. The parameters of Eqs. (9) and (10) are defined as follows:

$\hat{p}_{N_p}$ = probability that N_p police vehicles are free to conduct the search

N_p = number of police vehicles conducting the search

v_S = average speed of a police vehicle (miles/hour)

d_S = detection diameter of a police vehicle (miles). If the truck is within $^{d}S/2$ of a police vehicle, it can be detected by that vehicle.

t = the total time spent by police in searching for a suspect truck (hours)

t_D = the delay time between the actual hijacking and search initiation (hours)

v_T = average speed of a suspect truck (miles/hour)

D = one side of fixed area patrolled by N police vehicles (miles)

The numerator of the first term in Eq. (9) represents the area swept out by one patrol vehicle in time t. This is divided by the total area to be searched by each patrol vehicle to form a probability ratio of finding the truck up to this time. The area to be searched by each patrol vehicle is derived by assuming that the unknown area in which the truck can be located has side $2\,(t_D + t)\,v_T$, and that this area, equally divided among N_p patrol vehicles, represents an unknown area of side $\frac{2(t_D + t)\,v_T}{\sqrt{N_p}}$ for each vehicle. If a rectangular search of the type shown in Figure 1 is conducted by each patrol vehicle simultaneously, the total area to be searched is given by the denominator of the first term in Eq. (9). The probability of being able to assign N_p police vehicles to the search is given by Eq. (10) in terms of the probability that $(N - N_p)$ or fewer calls are being serviced. There is a small probability that those cars not assigned to the search will detect the truck, and this probability is represented by the second term in Eq. (9). This term ratios the effective detection area of unassigned vehicles (assuming $d_S << D$ and the detection areas are non overlapping) to the total area in which the truck may be found. For $t \leq \left(\frac{D}{2v_T} - t_D\right)$ the effective detection area of the unassigned vehicles is

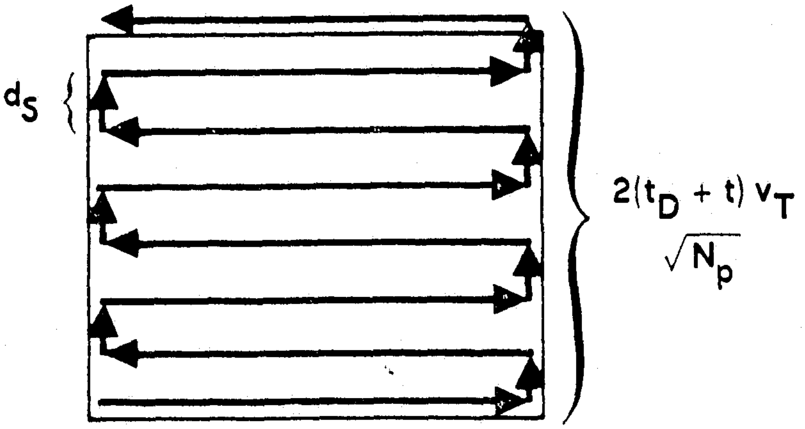

Figure G-1. Rectangular Police Vehicle Search

$$(N - N_p)\, d_S^{\,2} \left[\frac{4\,(t_D + t)^2\, v_T^{\,2}}{D^2}\right];\ (t \leq \frac{D}{2v_T} - t_D),$$

since not all of the vehicles in area D^2 have a chance to be in the trucks unknown area. When $t > (\frac{D}{2v_T} - t_D)$ the effective detection area becomes

$$(N - N_p)\, d_S 2/D^2 \quad ; \quad (t > \frac{D}{2v_T} - t_D) \quad .$$

Thus as the truck's unknown area, $4\,(t + t_D)^2\, v_T^{\,2}$, grows the probability of unassigned vehicle detection is

$$\frac{(N - N_p)\, d_S^{\,2}}{4\,(t_D + t)^2\, v_T^{\,2}} \left[\frac{4(t_D + t)^2\, v_T^{\,2}}{D^2}\right] \quad ; \quad (t \leq \frac{D}{2v_T} - t_D)$$

$$\frac{(N - N_p)\, d_S^{\,2}}{4\,(t_D + t)^2\, v_T^{\,2}} \quad ; \quad (t > \frac{D}{2v_T} - t_D)$$

or

$$\frac{(N - N_p)\, d_S^{\,2}}{\max\left| D^2,\ 4\,(t_D + t)^2\, v_T 2\right|}$$

4. Random Search Parameter Studies

A couple of test case parameter studies were run, by using the model presented in Section 3., to determine the sensitivity of pd(t) to the model parameters, and to gauge the effectiveness of the random search procedure in locating a truck.

Case I considers a five car search for a hijacked truck using the following input parameter values:

v_S = 30 miles/hour

d_S = 0.01893 miles (100 feet)

N = 30

N_p = 5

ρ = 0.7

t_D = 0.5 hour

D = 6.29 miles

v_T = 15 miles/hour

The values of N and D were chosen to coincide with average police car densities in the five largest metropolitan areas of the United States.[12] The single car utility ρ was chosen so that a low finite probability of not being able to send at least one police car would exist.* The probability of no police cars being available when a call comes in is given by p_{nc}, where

$$p_{nc} = 1 - \sum_{i=N}^{\infty} p_i \quad . \tag{11}$$

The function $p_{nc}(\rho)$ is plotted in Figure G-2 for the cases when N=2, N=12, and N=30. It can be seen that as the number of police vehicles increases, the single car utility can be made larger before system saturation takes place

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*Data gathered in New York[13] indicates that $\rho = 0.3$ is more realistic, but the value $\rho = .7$ is chosen for the reasons stated above, and because of a conservative police response probability.

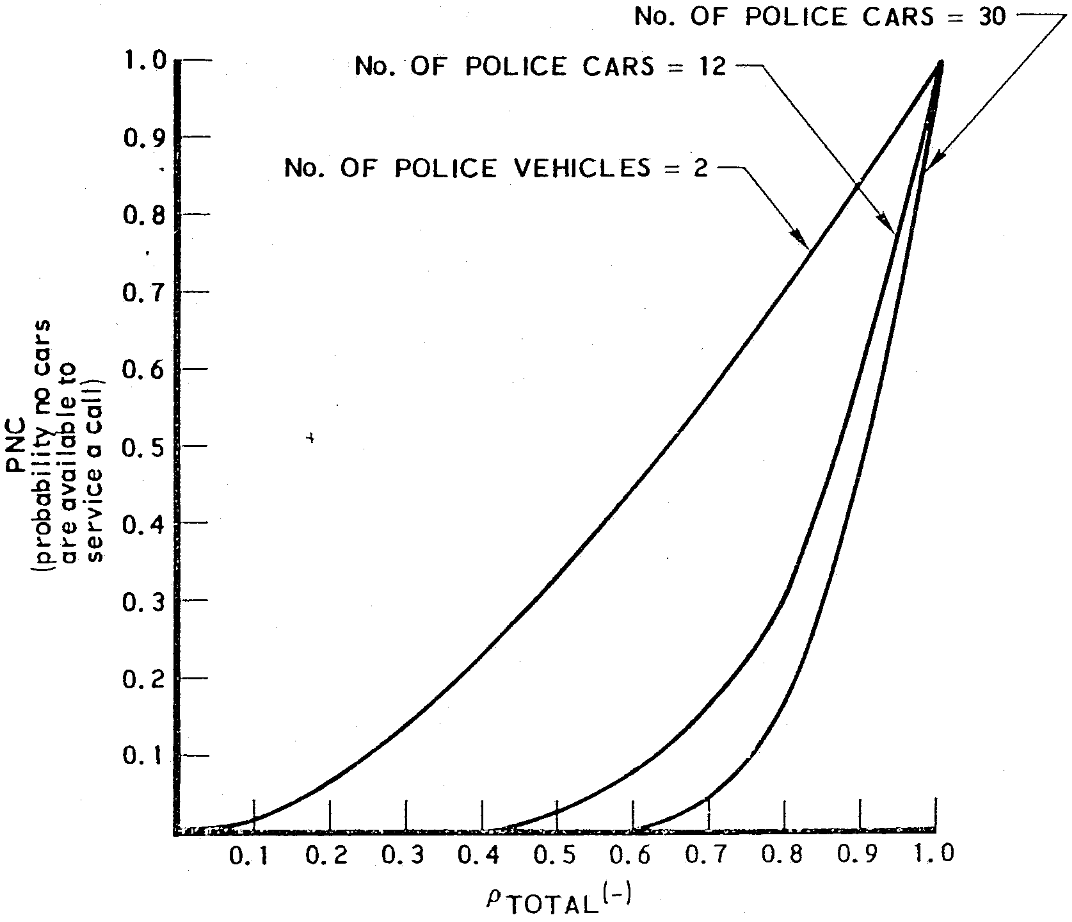

Figure G-2. Probability of Number of Cars Available Versus Single Car Utility (i.e., before p_{nc} becomes large). The other parameters were varied one at a time from their nominal values to find their influence on pd (t).

For the nominal case, the second term in pd (t) is small and will be assumed constant at $\frac{(N - N_p) d_S 2}{D^2}$. The first term has a unique maximum at $t = t_D$. Thus the maximum probability of detection occurs t_D hours after the search begins or $2t_D$ hours after the hijacking begins. After this time, the probability of detection decreases in inverse proportion to the time of search. Therefore, in evaluating the results of the parameter studies, capture was assumed if pd (t) = 0.9 for some t. If pd (t) $\neq 0.9$ $(0 \leq t \leq t_D)$ it was assumed that the entire patrol area would be searched before giving up the chase. Using these criteria v_S, d_S, N_p, t_D, and v_T were varied and pd (t_D) was plotted as a function of each parameter. The time taken to search the entire patrol area in the manner shown in Figure G-1 is T_S, where*

$$T_S = \left\{ HI \left[\frac{D}{d_S \sqrt{N_p}} \right] + 2 \right\} \frac{D}{\sqrt{N_p}\, v_S} \quad . \tag{12}$$

Plots of T_S and pd (t_D) as functions of the varied parameters appear in Figures G-3, G-4, and G-5.

It is apparent from these plots that the probability of detection using the random search approach is very low indeed. Without a hijack alarm system,

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*HI [X] = lowest integer value above X. This function is necessary since it is not practical to consider a fractional transversal of the search area.

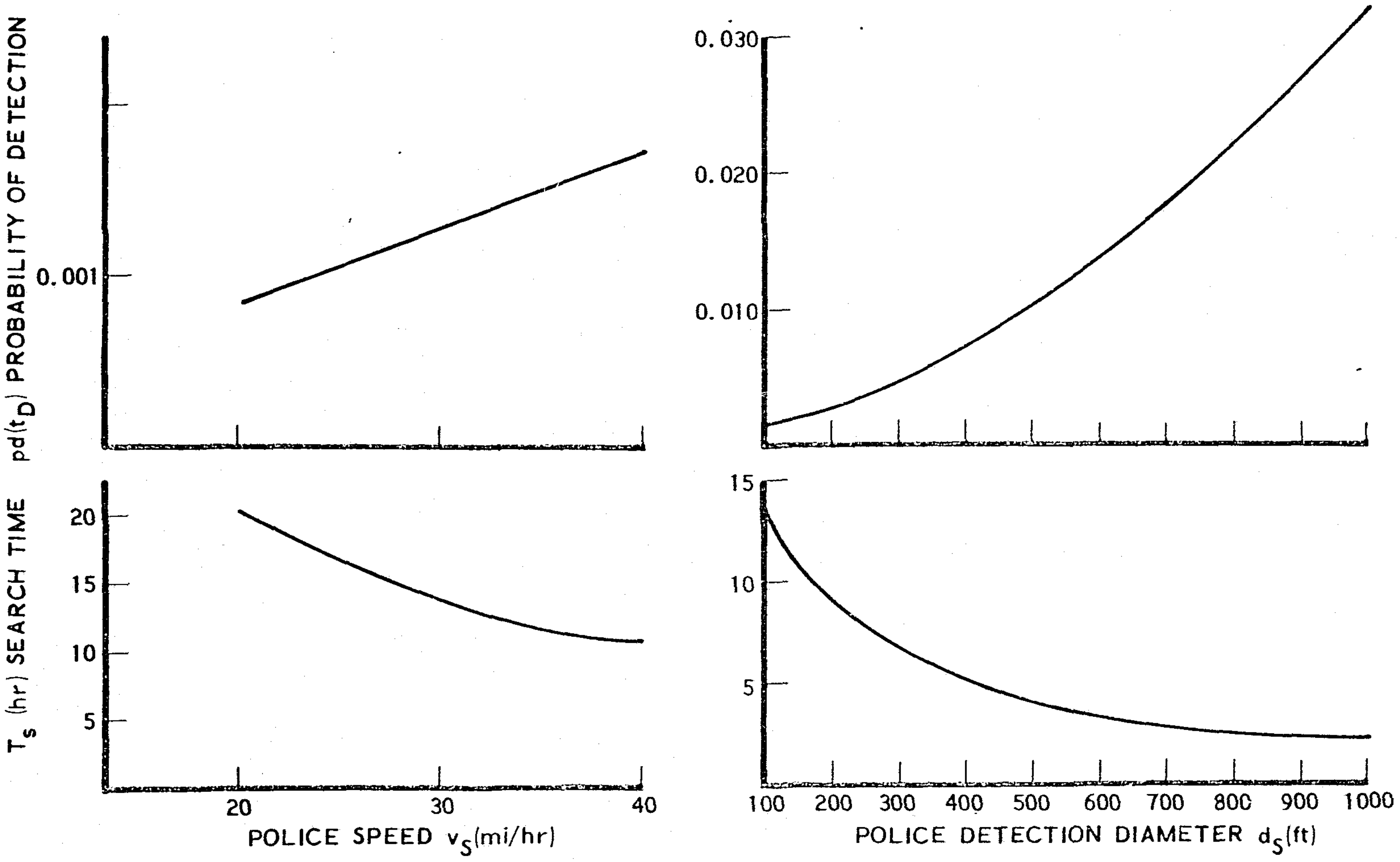

Figure G-3. Probability of Detection and Search Time Versus Police Speed and Police Detection Diameter

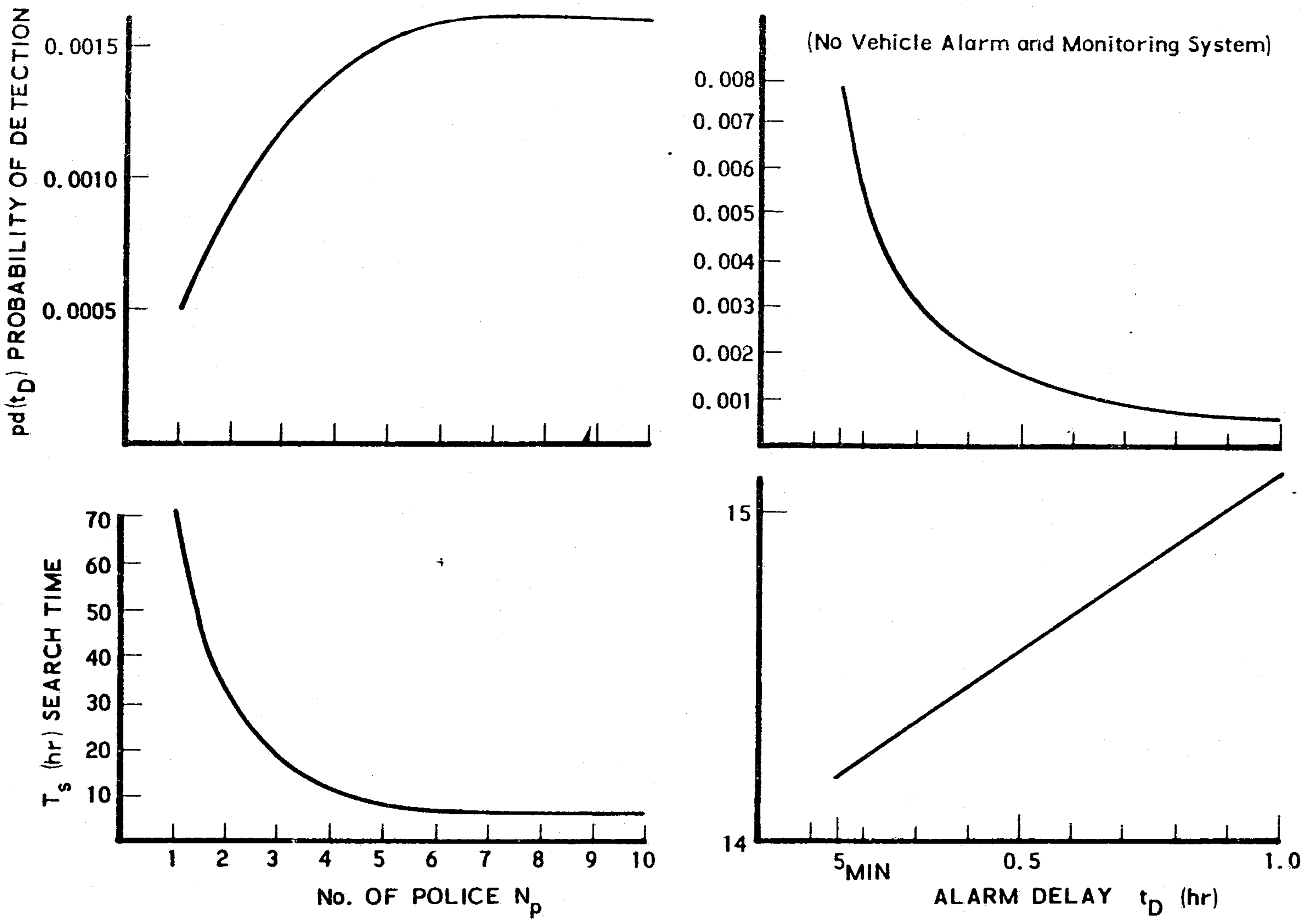

Figure G-4. Probability of Detection and Search Time Versus Number of Police and Alarm Delay Time

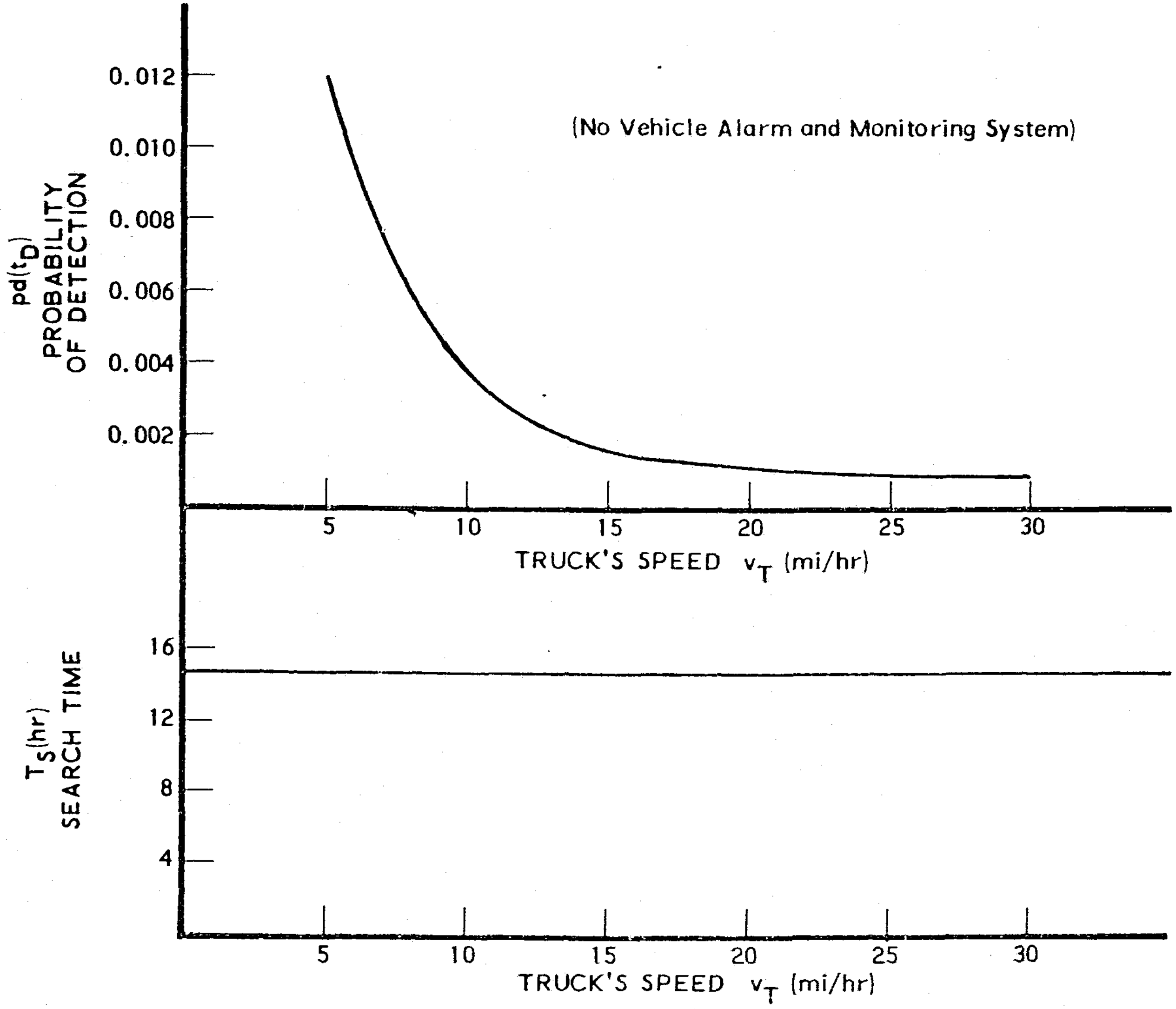

Figure G-5. Probability of Detection and Search Time Versus Truck's Speed it is very reasonable to assume delay times on the order of one-half hour to an hour before a truck is missed. Figure G-4 shows the sensitivity of pd (t_D) to t_D to be very low in this region. Adding more police cars to the search does not significantly increase pd (t_D) as seen in Figure G-4, and there is a practical limit to the number of cars which can be spared for such a lengthy search. Figure G-3 shows that increasing the police car's detection diameter and speed improves the probability of detection, but here again there are practical limits to these parameter values in an urban environment. Figure G-5 shows that if the truck has any speed at all, which will certainly be greater than 5 miles/hour, the probability of detection is small. The time needed to search the total patrol area is independent of v_T as can be seen by looking at Eq. (12). The time required for a thorough search of the patrol area, T_S, is seen to be at least an order of magnitude too high in all cases. This method of detection, even with the optimistic assumptions made, is clearly unacceptable.

A second nominal case which assumes parameter values suitable for a helicopter search was also used as a baseline case for a parameter study. The nominal values for Case II are given below:

v_S = 90 miles/hour
d_S = 0.25 mile
N = 2
N_p = 1
ρ = 0.2

t_D = 0.5 hour

D = 6.29 miles

v_T = 15 miles/hour

Only those parameter values which are related to the helicopter system are changed from Case I to Case II (e.g., v_S, d_S, N, N_p, and ρ). The results of plotting pd (t_D) and T_S versus the parameters are shown by Figures G-6 and G-7. In this case the plots versus N_p were not produced, because of the limited range of this parameter. Although the probabilities of detection are higher and the search times lower, the advantage of increased speed and detection diameter are mitigated by the lower number of search vehicles, and the results again fall far short of acceptable standards.

It would appear that the random search procedure is not feasible under the assumptions made in this study. The probability of truck detection is far too small for the amount of effort expended, and increasing the police vehicle speed and detection diameter within the limits of reason does not appear to hold the promise of significant improvement. Consequently, the need for an improved method of hijack detection and truck monitoring is indicated.

5. The Pursuit/Search Model

If one considers the possibility of sounding an automatic hijack alarm and monitoring the suspect truck's position so that the police are aware of it to within a specified accuracy, a model which includes a pursuit phase must be formulated. The first step toward this goal is to consider a one vehicle response according to pursuit scenario B of Section 1. This entails a response to a fixed point followed by a running pursuit along the truck's path and a

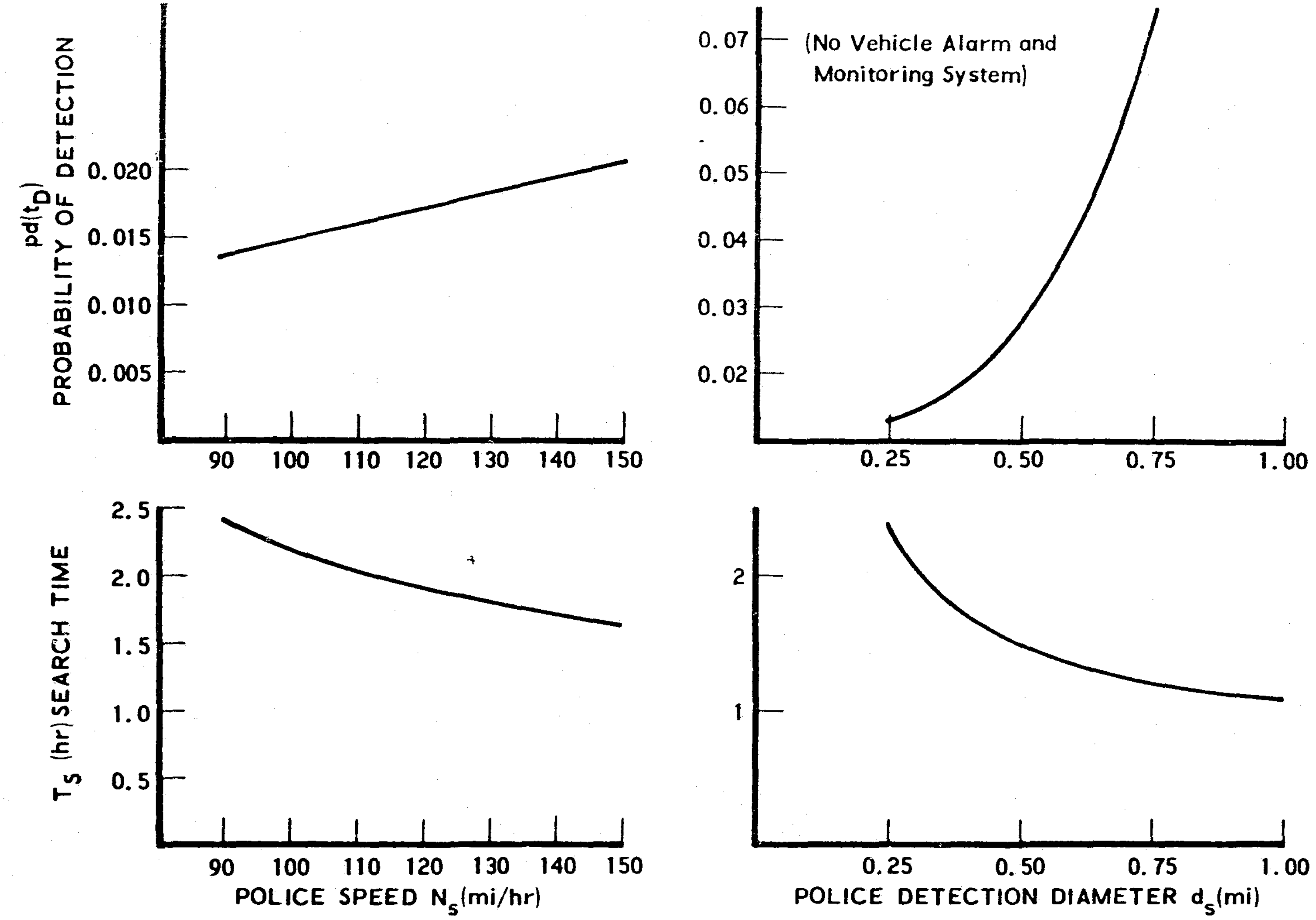

Figure G-6. Probability of Detection and Search Time Versus Police Speed and Police Detection Diameter

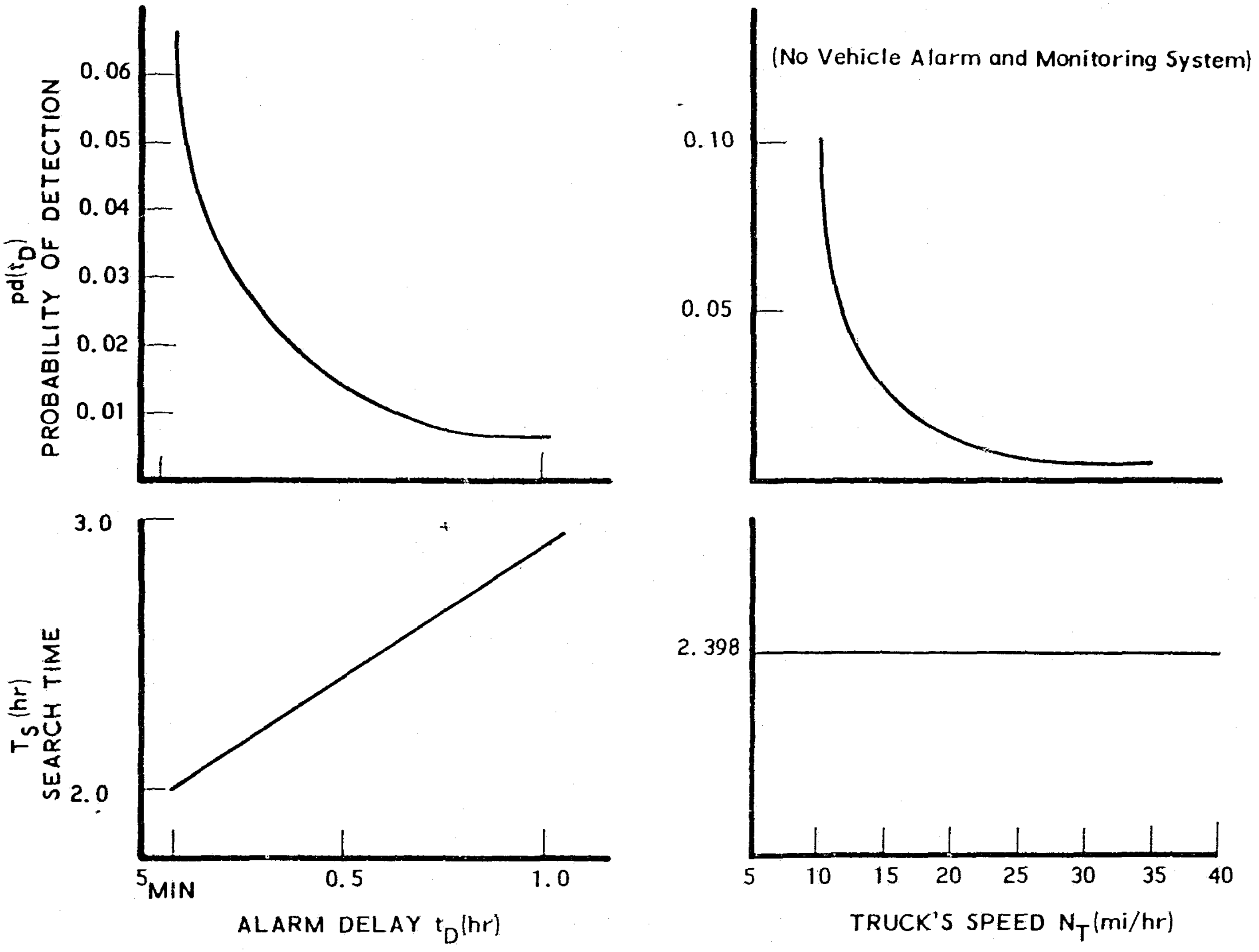

Figure G-7. Probability of Detection and Search Time Versus Alarm Delay Time and Truck's Speed random search in an uncertain area about the truck. As the model develops, it will become clear that pursuit scenario A is actually a special case of scenario B (i.e., the case for which the truck's velocity is zero throughout the pursuit and search).

The total time used by a police vehicle in locating a suspect vehicle is t_T,

$$t_T = t_D + t_{FP} + t_{RP} + t_S \quad , \tag{13}$$

where

t_D = delay time between start of hijacking and the first report to a responding police vehicle (hours)

t_{FP} = fixed point pursuit time required for the police vehicle to reach the point where the hijack occurs (hours)

t_{RP} = running pursuit time required for the police vehicle to trace the truck's route and overtake the suspect (hours)

t_S = search time required to locate the truck within an uncertain area (hours)

Under the most general circumstances the four times, or the right-hand side of Eq. (13), would be independent random variables, and the probability density function for t_T would be the multiple convolution of the density functions for these four times. In order to simplify the analysis, however, the following assumptions are made:

- The delay time t_D is a constant nonrandom variable
- The truck velocity is constant throughout the pursuit and search

The first assumption is valid if the alarm relay system (i.e., the police alarm receptionist and police dispatcher) is not saturated with calls and there are police vehicles free to respond. In such an unsaturated state the alarm relay time should be fairly constant and small in comparison with the other times involved. The second assumption is in line with hijack scenario (v) of Section 1. for a nonzero truck velocity and with scenario (iv) for a zero truck velocity. This assumption also allows t_{rp} to be expressed in terms of t_D and t_{FP} via the relationship

$$(t_D + t_{FP} + t_{RP})\, v_T = v_S\, t_{RP} \quad , \tag{14}$$

which states that the distances covered by the truck and police vehicle from the initial hijack point to the end of the pursuit are the same. By using Eq. (14) to solve for t_{RP}, the following equation for t_T results

$$t_T = t_D \left[\frac{v_S}{(v_S - v_T)}\right] + t_P + t_S \quad , \tag{15}$$

$$t_P \triangleq t_{FP} \left[\frac{v_S}{(v_S - v_T)}\right]$$

where t_{FP} and t_S are random variables, t_D is deterministic, and t_P is the pursuit time.

The single vehicle probability density function for t_{FP} was derived previously in Reference 14. This density function was derived under the assumptions that the police vehicle and hijack alarm point are uniformly distributed in the patrol area D^2 and that the police vehicle response follows a rectangular route in accordance with urban traffic routes. These assumptions will be maintained from here on in the present study. An adjustment to the model would be necessary if police vehicles other than land vehicles are to be considered (e. g., helicopters) although a conservative estimate of the helicopter pursuit problem might be obtained from the present model. The response time density function for t_{FP} is[14]

$$p_{FP}(t) = \begin{cases} f_1(t) = \left[4K^2t - 4K^3t^2 + \frac{2}{3}K^4t^3\right] & ;\ (0 \le t \le t_1) \\ f_2(t) = \left[\frac{16}{3}K - 8K^2t + 4K^3t^2 - \frac{2}{3}K^4t^3\right] & ;\ (t_1 < t \le t_2) \\ 0 & ;\ \text{otherwise} \end{cases} \qquad (16)$$

$$K = \frac{v_S}{D}$$

$$t_1 = \frac{D}{v_S}$$

$$t_2 = \frac{2D}{v_S}$$

Thus the one car response model for t_P is

$$p_{FP}\left[\frac{t_P\,(v_S - v_T)}{v_S}\right]$$

Let d_T be defined as one side of a square area of uncertainty about the suspect truck. This parameter, d_t, may be thought of as the monitoring systems position accuracy. If a rectangular search of the type shown in

Figure G-1 is assumed, the total time to search the area $d_T^{\,2}$ is given by T_S, where

$$T_S = \frac{\left| HI\,[d_T/d_S] + 2 \right| d_T}{(v_S - v_T)} \tag{17}$$

In Eq. (17), HI* $[d_T/d_S] + 2\ d_T$ represents the total linear distance covered by the search, and $(v_S - v_T)$ is the effective search speed. Here, it is assumed that the police vehicle must use v_T to keep up with the truck and thus has at most $(v_S - v_T)$ left for searching. It will be assumed that the truck's position is uniformly distributed in $d_T^{\,2}$, so the density function on the search time is

$$\begin{array}{lll} p_S\,(t) = \dfrac{1}{T_S} & ; & (0 \leq t \leq T_S) \\ \qquad\quad o & ; & \text{otherwise} \end{array} \tag{18}$$

Now, the probability density function for t_T† is given by the convolution of $p_{FP}\left[\dfrac{t_P(v_S - v_T)}{v_S}\right]$ and P_S which yields

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*HI(X) = smallest integer greater than X

†The density function for t_T is actually shifted by $t_D\,\dfrac{v_S}{(v_S - v_T)}$ to the right along the time axis, since t_D is deterministic.

$$p_T(\xi) = \int_{-\infty}^{\infty} p_{FP}\left[\frac{(v_S - v_T)(\xi - \tau)}{v_S}\right] p_S(\tau)\, d\tau$$

$$= \frac{1}{T_S}\left\{\int_a^b f_2 \frac{(v_S - v_T)(\xi - \tau)}{v_S}\, d\tau\right.$$

$$\left. + \int_b^c f_1 \left[\frac{(v_S - v_T)(\xi - \tau)}{v_S}\right] d\tau\right\} \qquad (19)$$

$$a = \max\left[o,\ \xi - \frac{2D}{(v_S - v_T)}\right]$$

$$b = \min\left[T_S,\ \xi - \frac{D}{(v_S - v_T)}\right]$$

$$c = \min\left[\xi,\ T_S\right]$$

Thus,

$$p_T(\xi) = \frac{1}{T_S}\left\{\frac{v_S}{D}\left[\frac{16}{3}(b - a) - 4k(\xi - a)^2 + 6k(\xi - b)^2 - 2k(\xi - c)^2\right.\right.$$

$$+ \frac{4}{3}k^2(\xi - a)^3 - \frac{8}{3}k^2(\xi - b)^3 + \frac{4}{3}k^2(\xi - c)^3$$

$$\left.\left. - \frac{1}{6}k^3(\xi - a)^4 + \frac{1}{3}k^3(\xi - b)^4 - \frac{1}{6}k^3(\xi - c)^4\right]\right\}, \qquad (20)$$

$$k = \frac{(v_S - v_T)}{D} \quad .$$

The distribution function for the total single car response time is by definition

$$P_T(t) \triangleq \int_0^t p_T(\xi)\, d\xi \quad ,$$

$$P_T(t) \triangleq \text{prob.}\ (t_T \leq t). \tag{21}$$

The distribution function for the car which can respond most quickly from the field of N patrol cars was developed in Reference (14) by using the one car distribution function. This optimal one car probability distribution is given by $P_T^*(t)$, where

$$P_T^*(t) = \sum_{k=1}^{N} p_{N-k}\left[1 - \left(1 - P_T(t)\right)^k\right] + \sum_{k=N}^{\infty} p_k\, P_T(t - t_{w_k}), \tag{22}$$

where the p_i $(i = 0, \ldots, \infty)$ are the call probabilities of Section 2., and the t_{w_k} are waiting times which are not zero when the system is saturated with calls. In the results to follow, the utilization ρ is chosen low enough to insure that the second summation in Eq. (22) is negligibly small (i.e., the system is not saturated). It is assumed that proper system design will take saturation into account and seek to minimize this undesirable property.

Besides the system design parameters already defined, the mean time between false alarms (MTBFA) is important in the way that it affects the police utility, ρ. If a given alarm system puts out a large number of false alarms in a short period of time (i.e., has a low MTBFA), the police utility will rise as time is spent investigating these calls. For the purposes of this study, it will be assumed that police utility is the following function of MTBFA

$$\rho = \rho o + \frac{CN_T \, t_{FA}}{N\ (MTBFA)} \quad , \qquad (23)$$

where

ρ = single vehicle police utility (fraction of time spent by each police vehicle in servicing calls)

ρo = baseline single vehicle police utility (fraction of time spent by each police vehicle in servicing other than false alarm calls)

C = alarm system coverage (fraction of all trucks in patrol area equipped with alarm system)

N_T = total number of trucks in patrol area

t_{FA} = average time spent in servicing a false alarm (hours)

N = total number of police vehicles in patrol area

MTBFA = average time between false alarms for a single alarm unit (hours)

6. Pursuit/Search Parameter Studies

As in the random search parameter studies, a baseline case is chosen, and parameter variations about this case are then performed. The criterion selected for evaluating the response is the 90 percentile response time (i.e., the time for which $P_T^*(t) = 0.90$). The distribution function $P_T^*(t)$ generally rises rapidly to the point $P_T^*(t) = .90$ and then flattens rapidly, which means that past this point, a small increase in the probability of response requires a large time increment. Thus, the time corresponding to the knee of the distribution curve was chosen.

The nominal or baseline case parameter values chosen for this study are as follows:

0.25 = C = fraction of trucks covered by the alarm system

4320 hours (6 months) = MTBFA = mean time between false alarms for a single alarm unit

0.11363 mile (600 feet) = d_T = one side of square area in which hijacked truck's position is uncertain

0.01893 mile (100 feet) = d_S = one side of square area within which police vehicle can detect a truck

0.5 hour = t_{FA} = average time spent in servicing a false alarm

0.7 = ρo = baseline single police vehicle utility

487 = N_T = number of trucks in patrolled area

30 = N = number of police vehicles in patrolled area

30 mi/hr = v_S = average speed of police vehicle during response

0 mi/hr = v_T = average speed of truck during hijacking

6.29 mile = D = one side of square area patrolled by police

0.0833 hour (5 min.) = t_D = delay time between hijacking and beginning of police response

The influence of MTBFA on police utility is plotted in Figure G-8 (i.e., $CN_T t_{FA}/N(\text{MTBFA})$ versus MTBFA) for the parameter values listed above. As can be seen by this plot, MTBFA does significantly influence the utility for values less than one week. It may be that a higher value is desired to decrease the ratio of false alarms to actual hijackings, since a high value of this ratio will adversely affect police morale. However, as a design parameter for the police response model, it does not appear to be as critical as it is for other police response alarm systems (e.g., a citizen's alarm system[14]) which have more potential users (by several orders of magnitude) and, thus, more alarm units. The MTBFA parameter has been set to six months for succeeding calculations, and its influence on response time is negligible. The base utility is chosen from Figure G-2 to reflect a situation near queuing saturation, which should be ideal if the best response is to be obtained for the least cost (i.e., the fewest police vehicles). The system utility should be close to the saturation point if one wishes to derive the maximum benefit from the police.

Since C and t_{FA} only influence the false alarm utility, which is in this case negligible, their values are selected to be reasonable and fixed for the study. The values of N, N_T, and D are derived from the average police and truck densities of the five largest metropolitan areas,[13] and the requirement that N not overflow the computer when used in the calculation of p_k in section II. Thus, N is chosen to be 30, D is computed using this value of N and the police density, and N_T is evaluated using D and the truck density. The delay time, t_D, is held fixed at what is considered a reasonable value for a

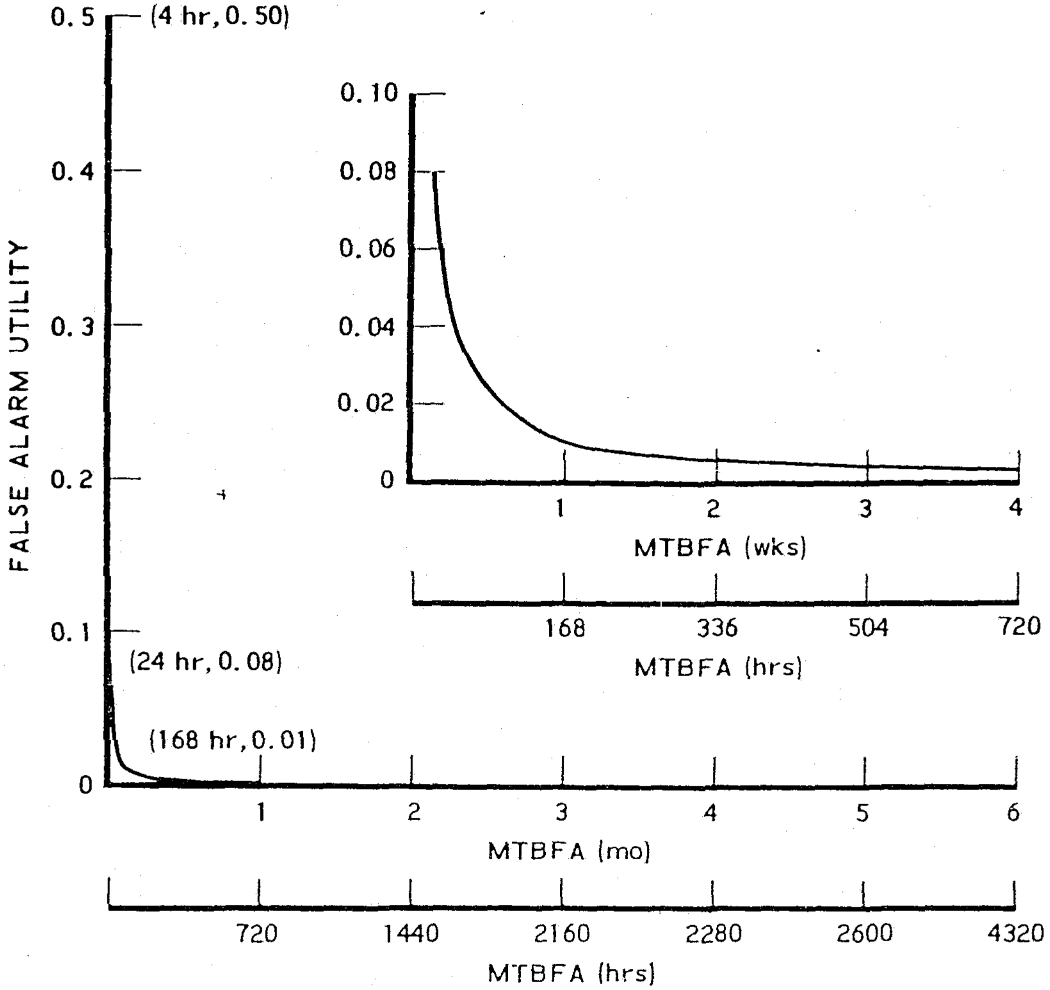

Figure G-8. Single Car False Alarm Utility Versus MTBFA for a Single Alarm Unit nonsaturated police relay communication channel. Since the relative speed of the police vehicle with respect to the truck is more important during the pursuit and search than either the truck or police speed alone, the police speed is held fixed at what seems a reasonable value and the truck speed is varied. For $v_T = o$, which is the nominal value, hijack scenario (iv) and pursuit scenario A are realized. Pursuit B and hijack (v) are represented by all cases for which $v_T \neq o$.

The variables v_T, d_T, and d_S are those to which the 90 percentile response time is most sensitive. Thus, these variables have been varied over a wide range of values to determine the nature and extent of their influence on t_{90} (the 90 percentile response time). The results of these studies are shown in Figures G-9, G-10, G-11 and G-12. Figure G-9 presents plots of t_{90} versus d_T and d_s which reflect the dependence of the response time on the uncertain search area about the truck and the detection area of the police vehicle. The baseline curve (d_s = 100 feet) shows that a serious increase in the response time does not occur until d_T reaches 1000 feet. Beyond this point, t_{90} increases rapidly. For larger values of d_S the effect is the same, but the degree of increase is much less.

Figure G-10 portrays a parameter study in which v_T and d_T are varied. As might be expected, the response time assymptotically approaches infinity as $v_T \longrightarrow v_S$. This would be unrealistic for a multiple intercept pursuit scheme, but it is reasonable to assume that a well designed pursuit system will employ a pursuit vehicle with a higher speed than the target vehicle. Here again, the dramatic effect of increasing d_T is shown clearly. In

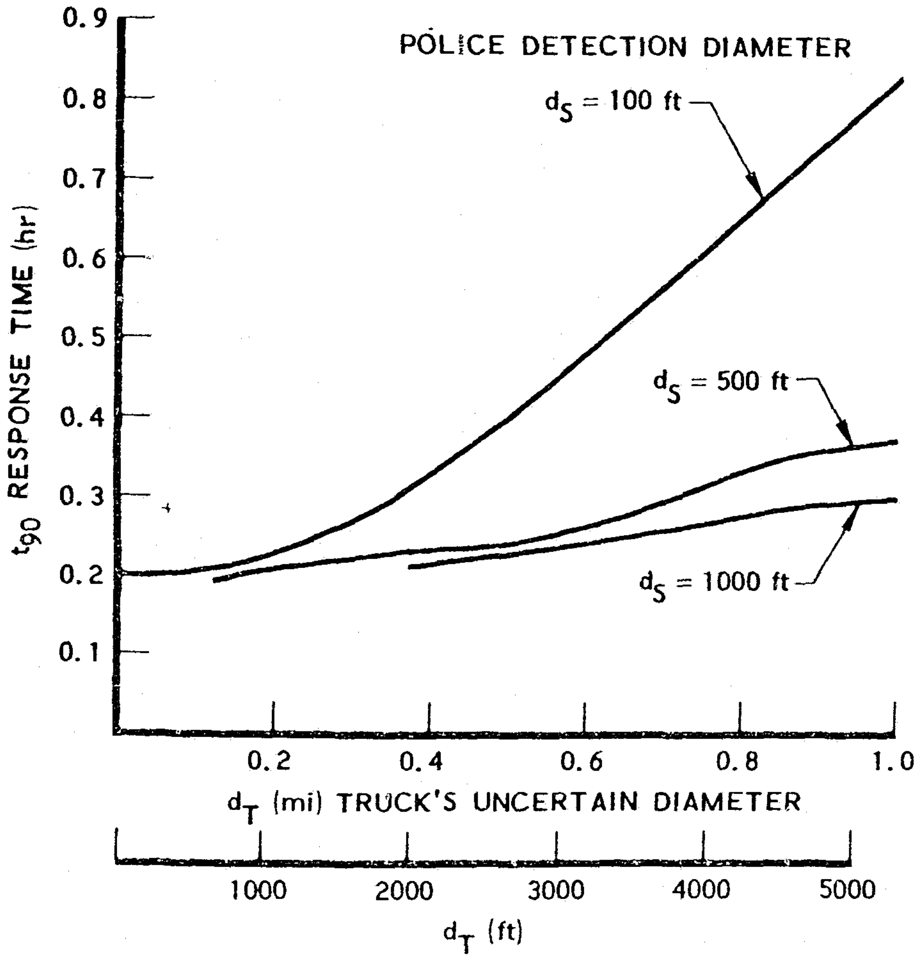

Figure G-9. Response Time Versus Truck's Uncertain Diameter and Police Detection Diameter

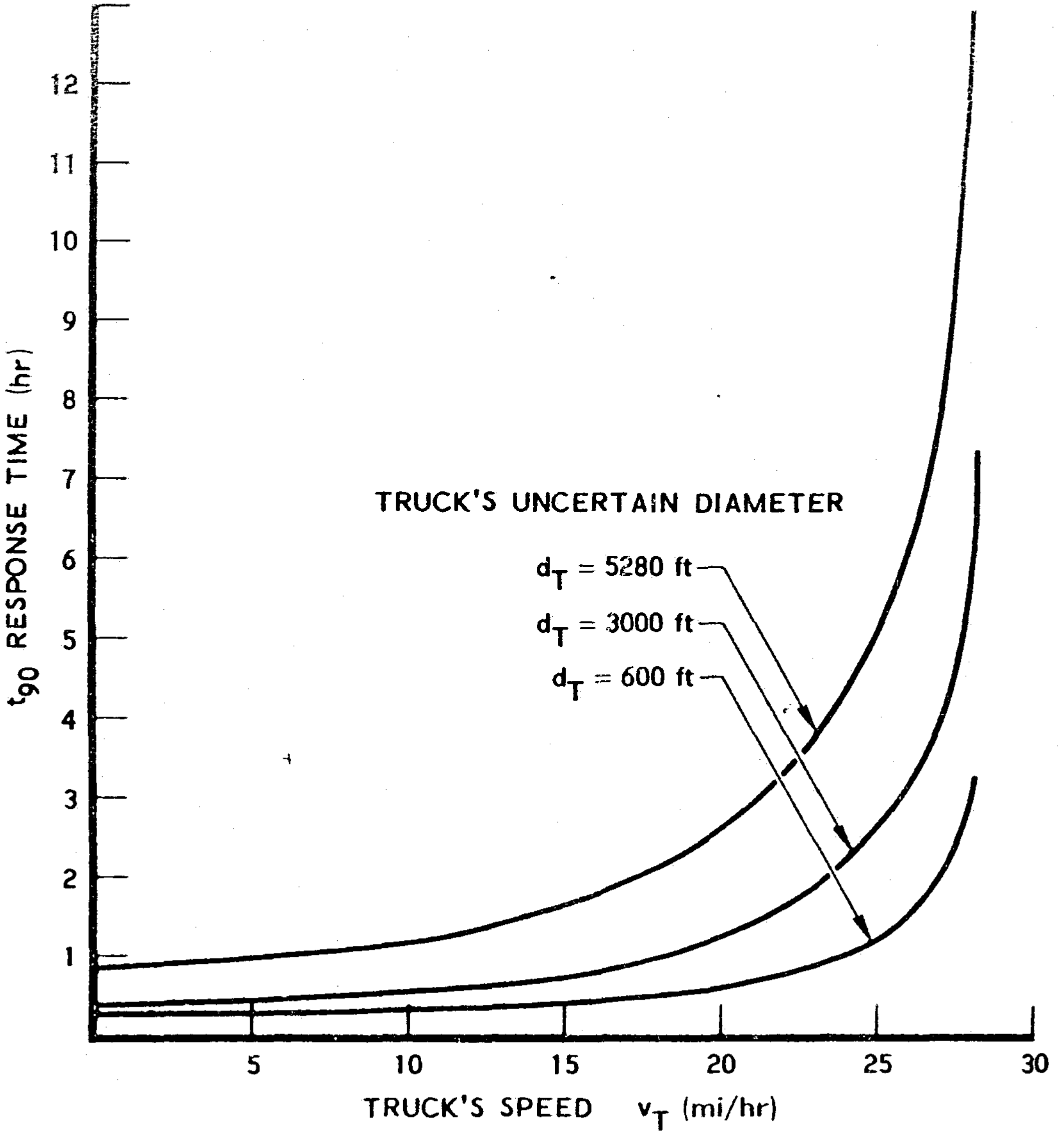

Figure G-10. Response Time Versus Truck's Speed and Truck's Uncertain Diameter

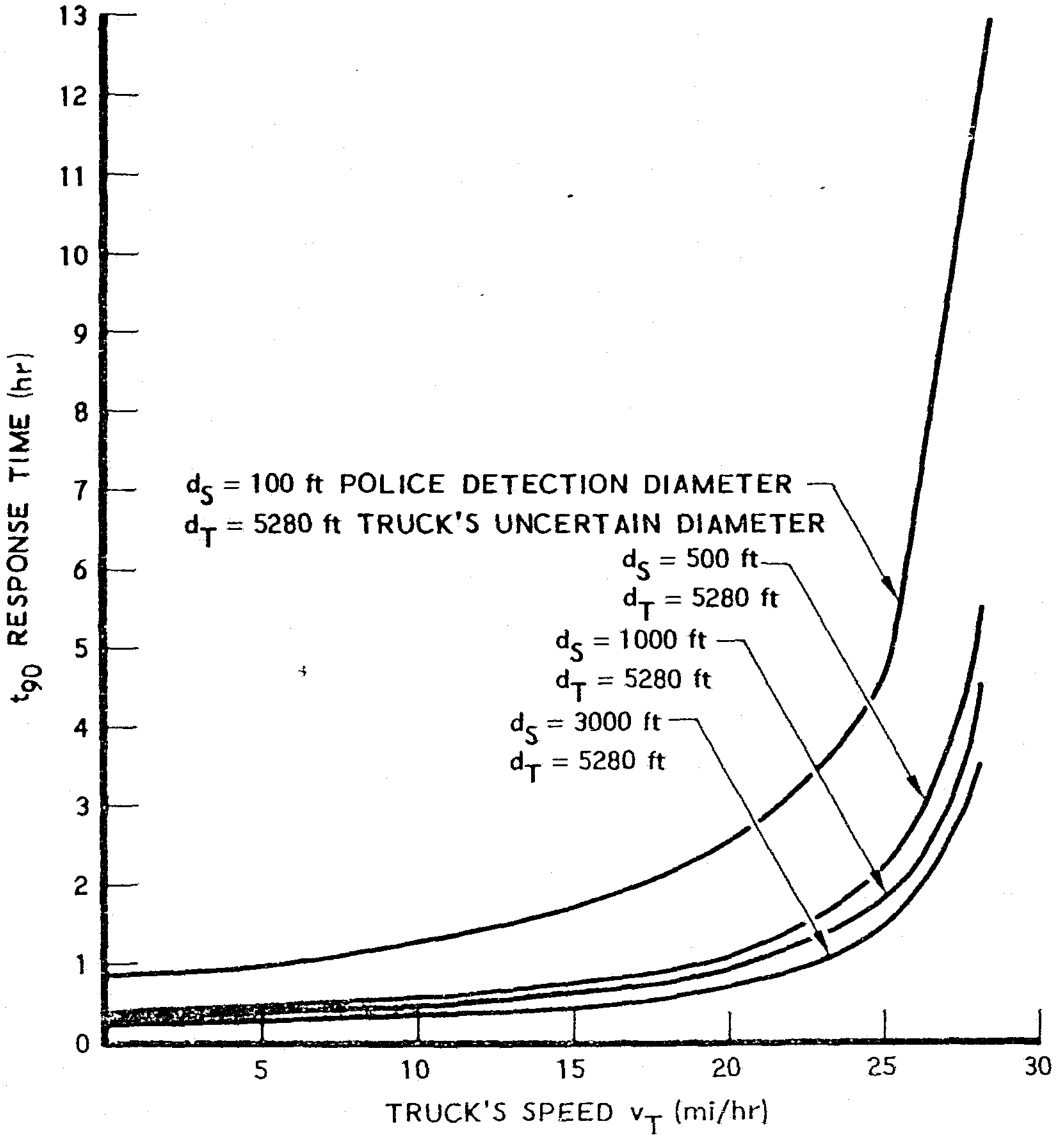

Figure G-11. Response Time Versus Truck's Speed and Police Detection Area Side

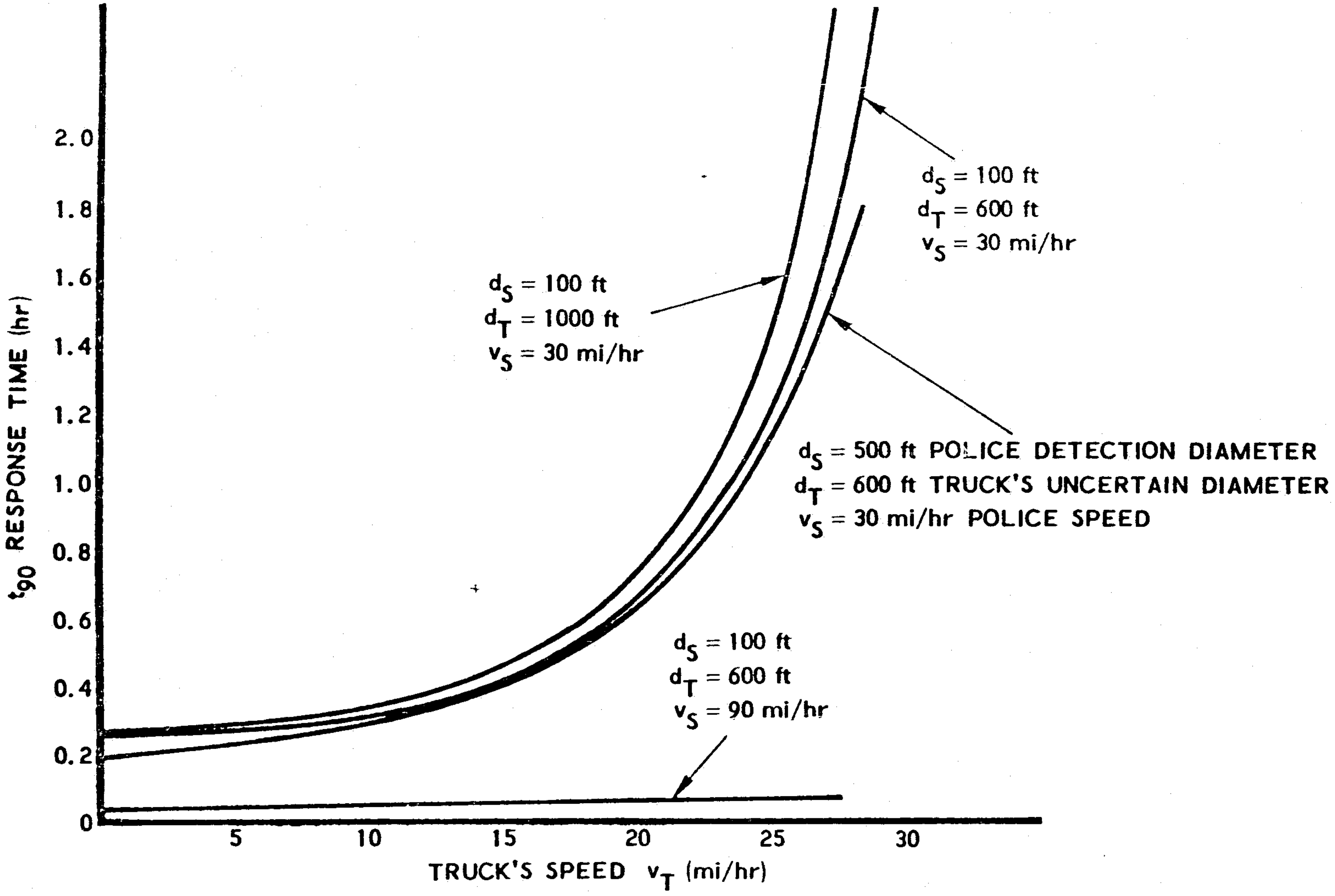

Figure G-12. Response Time Versus Truck's Speed, Truck's Uncertain Diameter, Police Detection Diameter, and Police Speed

Figure G-11 it can be seen that the response time is most sensitive to changes in d_S when d_S is less than 500 feet and d_T equals one mile. Also the influence of the police speed relative to the track is strongly shown once the difference in speeds goes below 20 miles/hour. Figure G-12 shows the influence of varying d_S and d_T separately. Here it can be seen that a 400-foot change in d_T about the nominal value has more effect on the response time than a similar change in d_S, but both effects are relatively small. The bottom curve in Figure G-12 shows the influence of increasing the police vehicle velocity to that characteristic of a helicopter. It was noted before that the square block pursuit algorithm was not designed to model a helicopter pursuit, but the results may nevertheless serve as a conservative approximation of this situation.

7. Conclusions

Based on the case studies presented in Sections 4. and 6., it is felt that three major conclusions may be drawn.

A. Without an automatic alarm and truck monitoring system, the chances of apprehending a hijacked truck are nil, and the police time expended in trying to apprehend a suspect truck is inordinately large. An alternate conclusion which might be drawn from the results of Section 4 is that the chances of apprehension are very low as long as the truck is able to move, since the unknown area in which the truck might be located grows as the truck's velocity.

B. The alarm system design parameter MTBFA does not appreciably affect police utility, and thus response time, for values above one week.

C. The police response time, assuming an automated alarm and truck monitoring system, is most dependent upon the relative police vehicle/ truck speed (v_S - t_T), the police vehicle detection diameter d_S, and the truck's position uncertainty diameter, d_T. For (v_S - v_T) values below 20 miles/hour the response time grows assymptotically to infinity as v_T approaches v_S. The values of d_T and d_S affect the search phase of the total response, and for large values of d_T (one mile) and small values of d_S (100 feet) the search can become very time consuming.

The above conclusions are, of course, subject to the assumptions and restrictions imposed. However, the assumptions made were designed to bracket the possible assumptions with best and worst case response time scenarios when possible. Certain conclusions suggest further work which might be undertaken to investigate the effect of alarm system parameters on performance indexes other than the police response time, and other conclusions point toward more complex response models which are also more realistic. For example, the second conclusion concerning MTBFA poses the question of how a one week MTBFA might affect police morale. If a low MTBFA causes a high ratio of false alarm to hijack alarm investigations, the police may be unwilling to live with such a "cry wolf" system. An alternate response model is also suggested by the third conclusion which lists (v_S - v_T) as an important design parameter. A more realistic cooperative police pursuit/search model would include the possibility of a multi-vehicle response, and the sensitivity of the response time to (v_S - v_T) is likely to be less for such a model. Similarly the benefits of police vehicles equipped with vehicle location systems would be explored. Such questions can be studied further if the answers are important to future alarm system programs.

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