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16. Abstract

This report delineates the preferred means, potential effectiveness, and estimated costs of carrying out anticipatory sensing of automobile collisions. Actuation of passive restraint systems requires only a small advance warning to extend the protection of such safety devices to impact speeds of 30 to 60 MPH - a range encompassing a large number of fatal and severe-injury accidents. This exampnation of means of achieving this function indicates that radar is the most promising crash sensing technique. Design, construction, and extensive test of prototype systems, accompanied by specific studies of component cost and reliability, show that an OEM price of $20 per unit (in volume of 10^6 per year) should be attainable for systems exhibiting extremely high electronic reliability. However, due to inherent limitations of radar, such sensors are likely to detect only 60% to 80% of the major collision objects encountered. A very low rate of inadvertent actuations is possible, occurring only in the course of certain minor (but high-speed) collisions. Potential benefits of full implementation are estimated to exceed prevention of 5000 deaths and 200,000 injuries annually. However, ultimate viability of anticipatory sensing systems will depend upon the use and effectiveness of improved vehicle structures and passive restraint systems.

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PREFACE

The work described in this report was performed in the context of an overall program at the Transportation Systems Center to evaluate anticipatory crash sensor concepts as applied to activation of automobile passive restraint systems. The program was sponsored by the National Highway Traffic Safety Administration, Office of Vehicle Structures Research, Department of Transportation. This program supports Government activities designed to promote greater safety on the nation's highways and reduce injury and fatalities in traffic accidents.

This research effort has involved many people. F. R. Holmstrom, while a TSC staff member, was responsible in large part for the original system conception; later, as a member of the Electrical Engineering Department, Lowell Technological Institute, Lowell, Mass., Dr Holmstrom carried out the studies on radar reflectivity and intervehicle interference which comprise Chapters IV and VII. Dr. E. Apgar, TSC, had primary responsibilities for the acoustic studies. M. Hazel contributed primarily through theoretical sensitivity calculations and estimation (from available statistics) of system effectiveness (Chapter VI); he prepared all appendices. R. Abbott's principal contribution was in the area of circuit design and evaluation; he was, in addition, responsible for management of the signal processor study (reported in Chapter 5). E. White and T. Newfell conducted circuit fabrication and a wide range of system test activities. Overall problem formulation and project direction was the responsibility of J. Hopkins.

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1. INTRODUCTION

1.1 BACKGROUND

Each year, approximately 55,000 people die in automobile accidents in the United States. The majority of the victims - approximately 63% - are occupants of passenger cars. Similar figures apply for injuries. Further examination of accident statistics shows that nearly half of these deaths result from frontal impacts.

Thus, improvement of vehicle crashworthiness, particularly with respect to frontal collisions, can quickly be identified as an area of crucial importance. Under the National Traffic and Motor Vehicle Safety Act (PL 89-563, September, 1966) the Secretary of Transportation is empowered to set Federal Motor Vehicle Safety Standards for motor vehicles manufactured for sale or use in the United States. This activity is carried out by the National Highway Traffic Safety Administration, which has issued a large number of such standards. One of these, FMVSS No. 208, Occupant Crash Protection is directly concerned with the problem of protection of passengers and driver in frontal and angled collisions, and ultimately represents one of the technically most challenging regulations yet promulgated.* In essence, FMVSS 208 will require, as of August 15, 1975, full occupant protection (defined by forces and accelerations on instrumented anthropometric dummies) for

*Details of this regulation, Standard No. 208; Occupant Crash Protection, will be found in Code of Federal Regulations, Title 49, Parts 200 - 999, Oct. 1, 1972, pages 488-496.

for fixed barrier collisions at up to 30 MPH.

The basic feasibility of this level of protection is clear, as indicated by several studies of seat-belt effectiveness. Unfortunately, seat belt usage has been disappointingly low in the United States (less than 4% for three-point belts). It has therefore, been the decision of NHTSA that the protection required by FMVSS 208 must be completely passive - no action by the occupants is to be necessary. This aspect of the regulation has required a major technological effort to achieve full system realization.

The major thrust of passive restraint development in the United States has been based on inflatable occupant restraint systems, commonly referred to as "air bags". The air-bag system of passive restraint is ingenious and complex. Porous cloth bags, normally folded and placed in containers in front of automobile occupant positions, are connected to manifolds through which nitrogen or other gases can be admitted. Nitrogen is stored at about 2000 pounds pressure in flasks that are connected to the manifolds; in addition, pyrotechnic gas generators can be provided as supplementary sources of gas to the manifolds. Sensors are provided to determine that an impact of potentially serious magnitude has occurred. When an impact above threshold is sensed, valves are actuated to release the stored nitrogen into the bags and/or fire the pyrotechnic gas generators. The air bags fill with gas and deploy abruptly in front of the vehicle occupants to cushion them and prevent their collisions with the vehicle interior. Deflation then occurs within less than one second.

The means of actuation most commonly used at present is mechanical deceleration sensing. In essence, a mass is constrained by a spring (or other restraining force) such that only a vehicle deceleration of 5 to 20 G will cause sufficient motion to close electrical contacts, triggering deployment. To avoid inadvertent actuation due to minor collisions or road irregularities, mechanical and electrical integration over a significant period of time (tens of msec.) is generally used, in conjunction with a three-fold series redundancy of the basic decelerometer structure. In order to respond only to deceleration of the entire vehicle and not to the sometimes violent motions of the smaller elements of the structure, these sensors are typically mounted on the firewall. The total response and integration time associated with such sensors can easily reach 20 to 40 msec., which limits the effectiveness of dynamic restraints, particularly for smaller cars and higher impact velocities.

Crash sensing is thus seen to be a crucial part of the operation of passive systems, upon which overall restraint performance is vitally dependent. A brief, highly simplified examination of collision dynamics helps in clarifying the interaction of air bag and sensor characteristics in determining overall effectiveness. Such a discussion follows.

1.2 COLLISION DYNAMICS

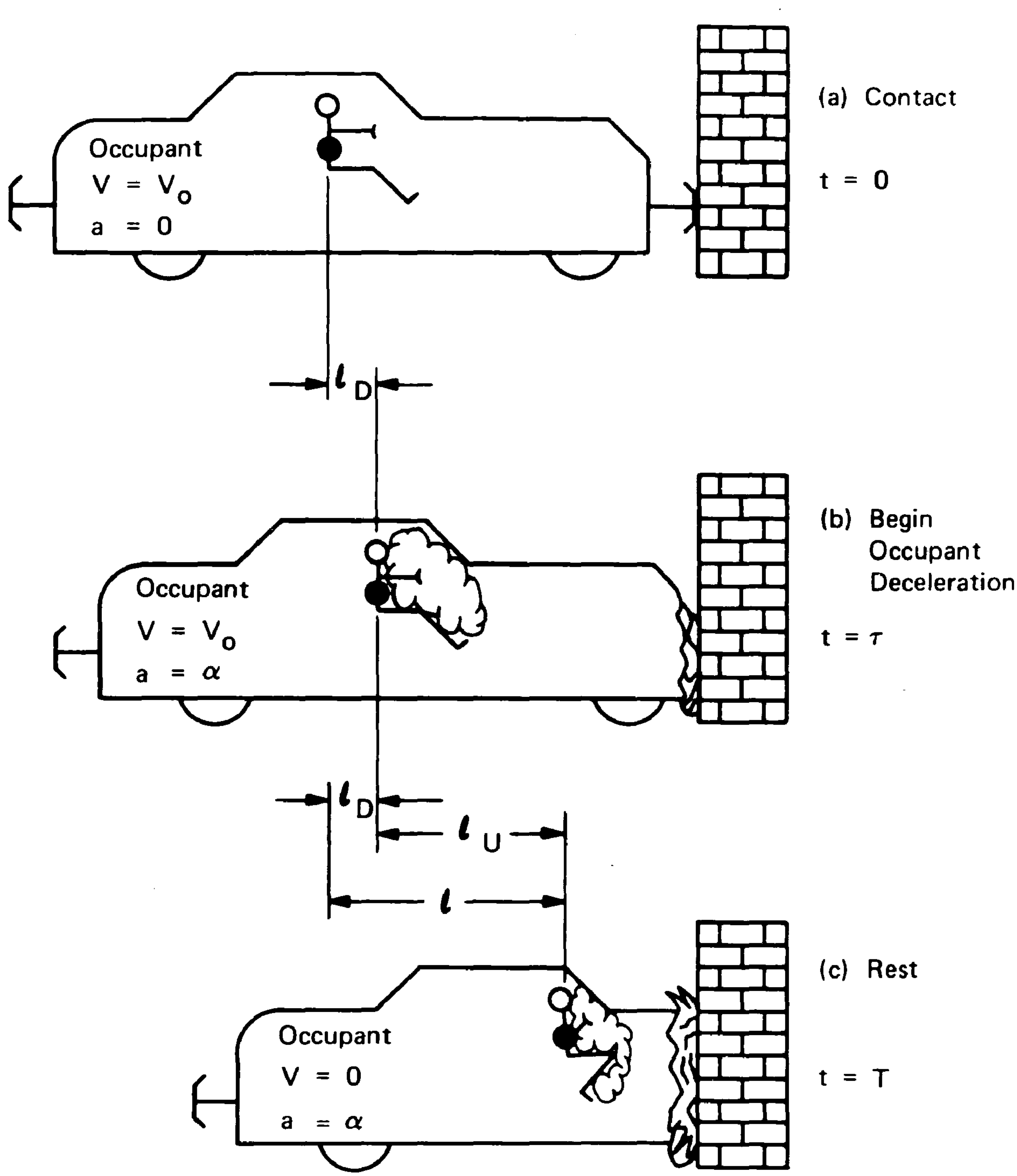
The analysis given here is based upon a very much simplified model of what is actually an extremely complex event. However, it is of sufficient validity to give both quantitative and qualtitative insight into factors necessary for protection in frontal barrier crashes. The basic crash sequence is illustrated in Figure 1-1. The time delay between first contact of vehicle with barrier ($t = 0$) and full restraint deployment (onset of occupant deceleration) is referred to as t_d, during which time the occupant travels a distance ℓ_d at the initial velocity v_o. The acceleration is assumed to have a half-sine form:

$$a = a_p \sin(\pi \frac{t}{\tau}), \text{ with } 0 \leq t \leq \tau,$$

where a_p is the peak acceleration and τ is the time during which deceleration occurs - from $t = t_d$ until the system is at rest. The quantity ultimately of interest is the maximum initial velocity, v_{om}, for which a specified a_p and total allowed deceleration distance ℓ permit reduction of occupant velocity from v_{om} to zero. Relatively straightforward integration and algebra, with appropriate boundary conditions, yield a simple quadratic equation for v_{om}:

$$v_{om}^2 + (\frac{4a_p t_d}{\pi}) v_{om} - (4 \frac{a_p \ell}{\pi}) = 0$$

However, one further correction is required. The deceleration distance ℓ is composed of available space within the passenger compartment (which is assumed to be basically undeformed by the collision) ℓ', plus that distance resulting from crushing of the front portion of the vehicle. This latter distance, ℓ_o, will clearly be a function of impact speed, and it is adequate for these purposes to assume simple proportionality: $\ell_o = t_\ell v_{om}$,



Simplified crash sequence.

Figure 1-1 Basic Collision Sequence

where t_ℓ is generally found to be in the range of .03 to .06 seconds. (This corresponds to .5 to 1.0 inches of crush per MPH.) The above equation for v_{om} may then be rewritten:

$$v_{om}^2 = \left(\frac{4a_p t'}{\pi}\right) v_{om} - \left(\frac{4a_p \ell'}{\pi}\right) = 0$$

with $t' = t_d - t_\ell$.

In Figures 1-2 - 1-4, V_{om} is plotted as function of t', with a_p and ℓ' as parameters. These curves are thus quite general with respect to t_d and t_ℓ values. Peak decelerations of 20, 40, and 60 G are considered, even the last value being accepted as tolerable to humans. Values of .5, 1.5, and 2.5 feet are used for ℓ'. The 2.5 foot case is approximately the maximum likely in an average vehicle, with 1.5 perhaps more representative, due to the tendency of occupants to be thrown forward by hard braking just prior to an accident or during the initial crushing before full restraint deployment. The .5 foot case is of particular interest in connection with seat belts, for which one can expect little "ride down".

As a direct indication of the nature of the results embodied in Figures 1-2 - 1-4, some representative numbers are given in Table 1-1.

In spite of the simplifications inherent in this analysis, the results are in good agreement with empirical studies. As the acceleration pulse shape is varied from half-sine to square wave, the principal effect is a lowering of the required a_p for a given v_{om}. Note that the rms acceleration for a_p values of 40 and 60 G

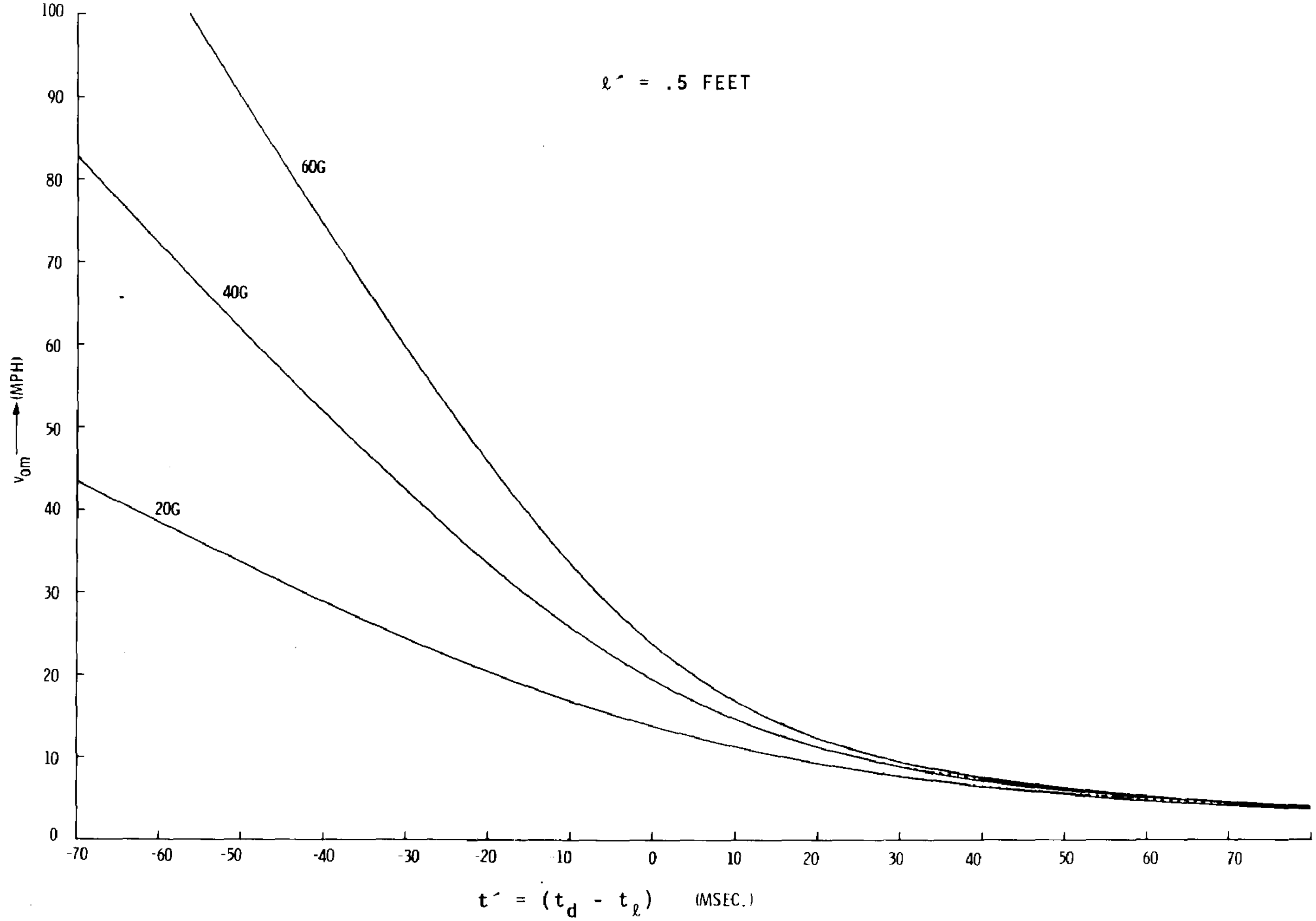


Figure 1-2 Maximum Tolerable Initial Velocity v_{om} as a Function of t_d -t

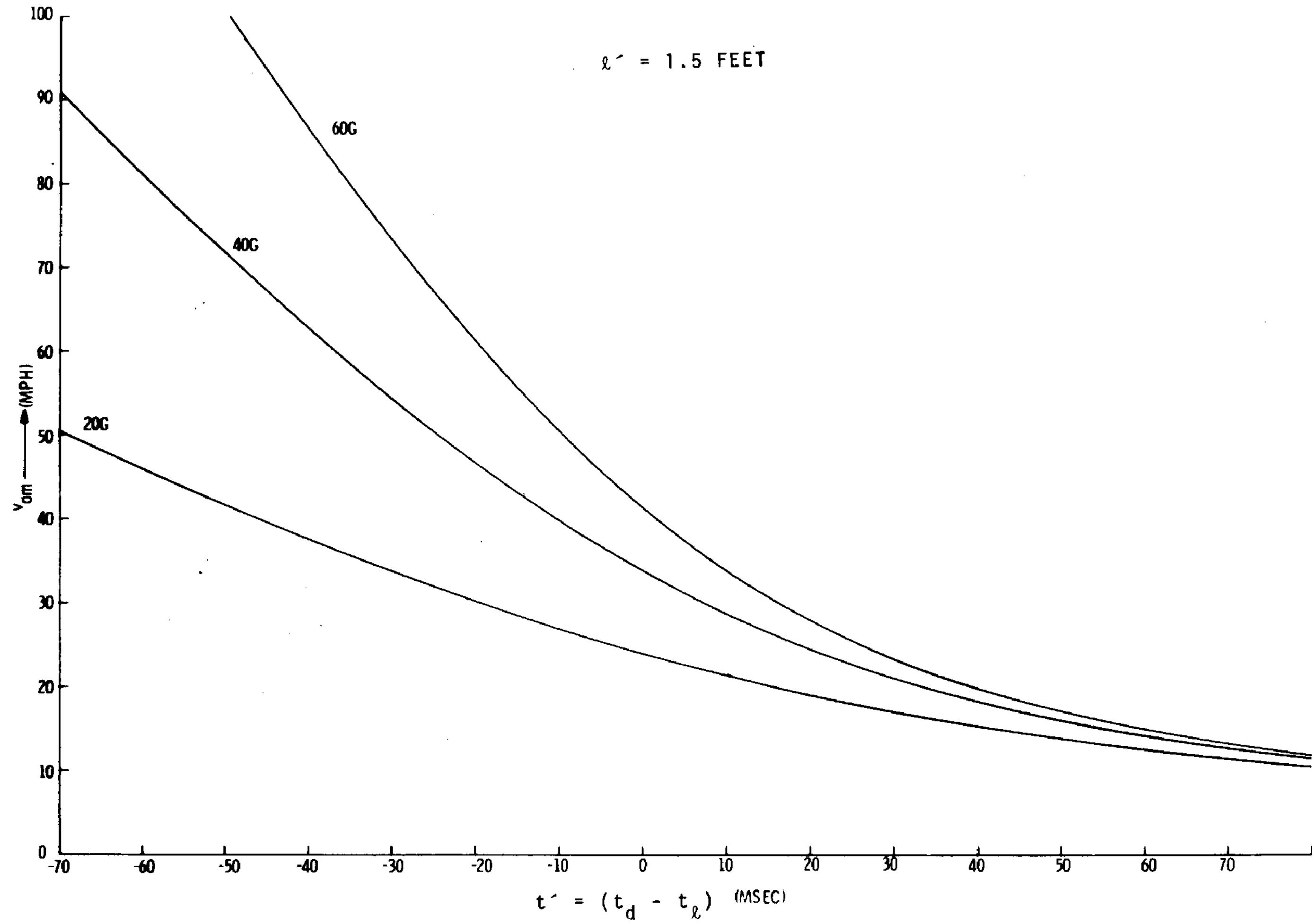


Figure 1-3 Maximum Tolerable Initial Velocity v_{om} as a Function of t_d -t

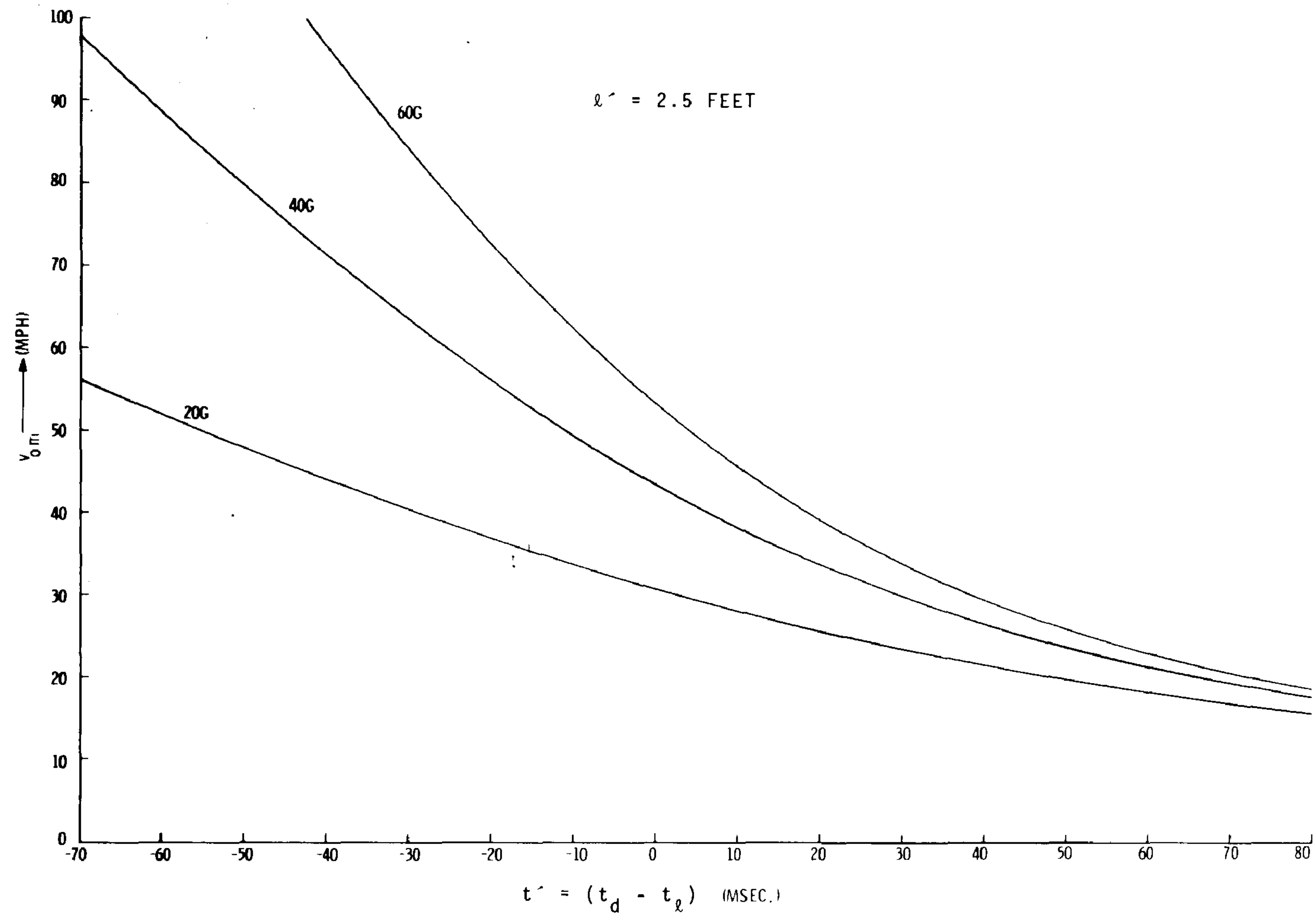


Figure 1-4 Maximum Tolerable Initial Velocity v_{om} as a Function of t_d-t

TABLE 1-1 MAXIMUM TOLERABLE IMPACT SPEED AND ASSOCIATED CRUSH DISTANCE FOR SELECTED a_p AND t_d; $\ell' = 1.5'$, $t_\ell = 35$ ms

a_p (G) \ t_d (msec)	50	25	0	
60	30.6	45.6	79.9	Tolerable Impact Speed (MPH)
40	26.5	36.6	58.5	
60	1.6	2.3	4.1	Crush Distance (feet)
40	1.4	1.9	3.0	

are approximately 28 and 42 G, respectively. The value used for t_ℓ (35 msec) is appropriate to a relatively rigid vehicle, and corresponds to a crush rate of .6 inches per MPH, or a 3-foot crush at 60 MPH. While substantially higher t_ℓ values are appropriate to "average" present-day vehicles, (approximately 1 inch/MPH, or t_ℓ = 55 msec), such deformation is unacceptable for intermediate and compact cars if high impact speeds are to be tolerable.

1.3 IMPLICATIONS OF ACCIDENT DATA

The implications of these results for automobile safety are seen when accident statistics are examined in terms of the distribution of impact velocities. Such data is presented in Figure 1-5 (adapted from ref. 2) with pertinent results summarized in Table 1-2.

It is immediately clear that the range of barrier-equivalent impact speeds of 30 - 50 MPH is of primary importance, particularly for reduction of fatalities, and there is a significant further gain in reaching 60 MPH. As found previously, achieving

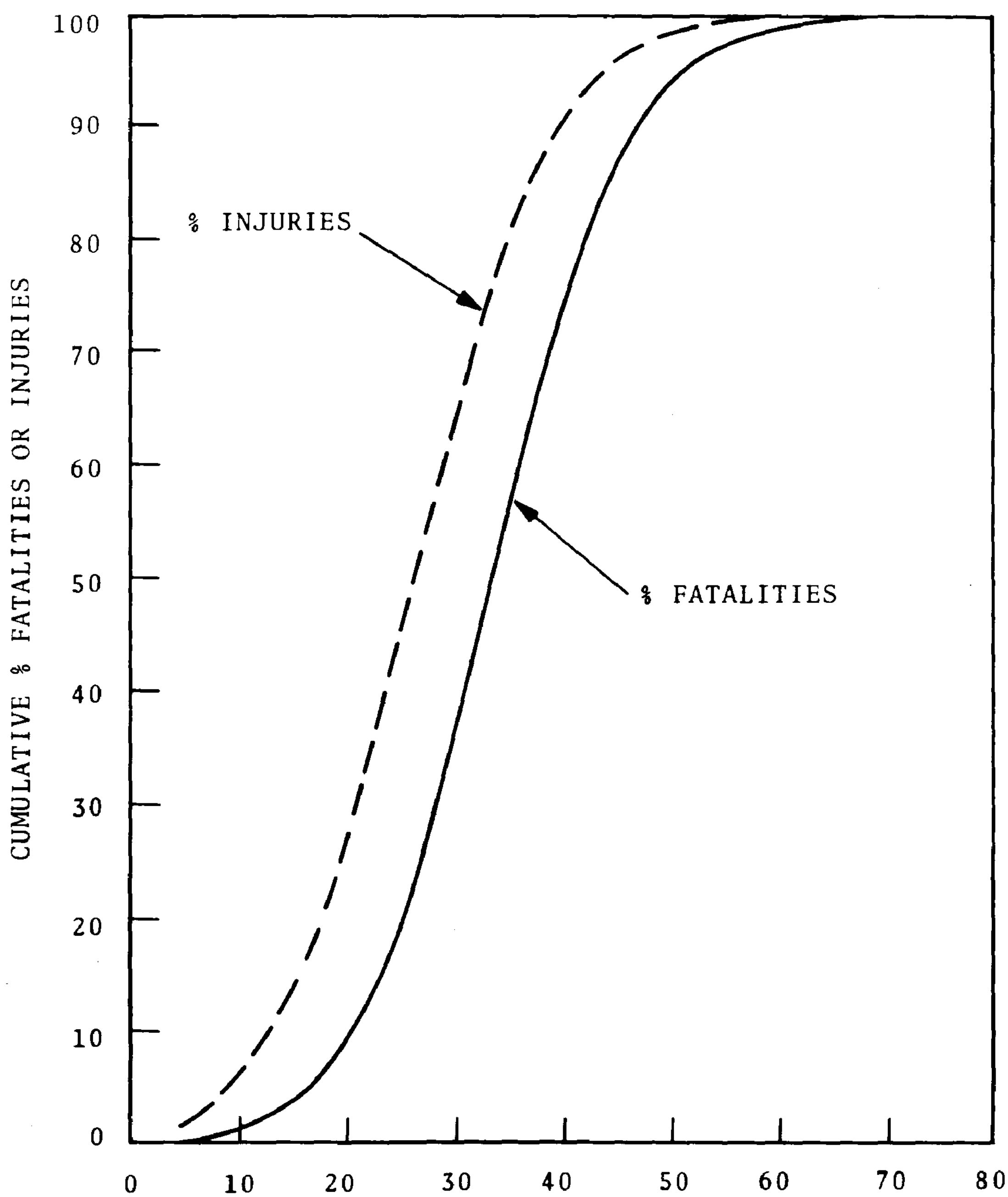


Figure 1-5 Cumulative Percentage of Fatalities and Injuries Within Equivalent Test Speed Range (From Ref. 2)

TABLE 1-2 PERCENTAGE OF TOTAL DEATHS AND INJURIES IN FRONTAL COLLISIONS IN VARIOUS RANGES OF BARRIER-EQUIVALENT IMPACT VELOCITIES

	0 - 30 MPH	30 - 50 MPH	50 - 60 MPH
% of total deaths	38%	55%	5%
% of total injuries	64%	34%	2%

this performance necessitates that the sensing and deployment time for passive restraint systems must be very small. It appears possible that mechanical impact sensing, in conjunction with aspirated air bags, may eventually approach the required performance specifications. However, the task is a very challenging one, and could require inflation characteristics which are not optimal at lower velocities. Alternatively, if some means could be found to sense the impending crash approximately 25 msec prior to impact (for example), a relatively moderate inflation rate and a_p would be acceptable. (60 MPH = 1 inch/msec, so a sensing distance of only 2' is adequate.) A final decision as to which course is preferable depends upon a number of general system considerations. However, an overall compromise is only possible when the viability, cost, and performance characteristics of potential anticipatory sensors can be estimated with some degree of confidence. It is in response to the need for such information that the research program described in this report has been carried out. The goal of this effort is delineation of the nature, operational characteristics, reliability, price, and probable effectiveness of an effective anticipatory crash sensor.

1.4 PROGRAM OBJECTIVES

The orientation of this program permits a somewhat different approach than that taken by industrial firms, particularly automobile manufacturers. We are not under compulsion to develop a total system suitable for mass production and installation 3 to 4 years from now, meeting standards already specified. We have the freedom to consider a longer time-span. We can consider in greater detail the more basic standards of overall reliability and cost-effectiveness, without being constrained by regulations necessarily prepared in advance of technical realization, and likely to change with time as different engineering constraints or technical possibilities emerge.

The basic operational requirements upon anticipatory sensors are discussed in Section 2-1. It is sufficient to state here that development of such sensors poses a problem of very considerable difficulty. The complexity of the task becomes apparent as one considers the great variety of obstacles with which collision is possible, many of which must not induce deployment. These latter include most animals, snowbanks, hedges, most fences and railings, blowing paper or other objects, small stones, curbs, swarms of birds or insects, and large objects of low mass, such as cartons and wooden crates. Even relatively rare occurrences must be considered due to the required near-zero false alarm rate. (Approximately three billion miles are driven daily in the United States; anything that can happen will occur frequently).

On the other hand, real collisions can also involve many different objects: rock, concrete, wood, both living and dead, and metal in many forms. Further, both real and false-alarm targets can occur wet or dry; encrusted in snow, ice, mud, or soot; under conditions of fog, darkness, or brilliant sunlight.

Within such constraints, as well as those of economics and operating environment, it is not obvious that any completely satisfactory system can be devised. However, even a negative conclusion of sufficient generality would be of value, particularly in determining future safety requirements. On the other hand, the possibility that a workable (if not ideal) system can be developed with its associated advantages, warrants the effort described in this study.

2. ANTICIPATORY SENSING: REQUIREMENTS AND TECHNIQUES

2.1 GENERAL CONSTRAINTS

There are a number of constraints which must be satisfied by any anticipatory crash sensor if it is to be viable in general automotive use. While thorough analysis and considerable development effort may be necessary in some cases to determine whether a particular concept or system is acceptable, it is useful to specify at the outset certain basic requirements which must be met by any practicable approach; they are listed below. Since almost any system is likely to include electrical and electronic aspects, particular attention is given to factors relevant to them.

a. High Reliability. The average age of automobiles is 5 to 6 years. It is by no means uncommon, particularly in certain regions, to find many vehicles more than 10 years old. Maintenance and periodic inspection are often either very limited or lacking entirely. At the same time, there is approximately a one-in-fifty chance that a given vehicle will be involved in a serious collision in a year interval. Thus, a very low failure rate must be achieved. However, this refers only to the question of failure to operate when needed. As will be indicated later, any failure mode resulting in inadvertent restraint deployment will be a far different and more serious matter. In both categories, the reliability requirements far exceed those normally imposed on automotive systems, and probably represent the most difficult constraints to meet.

There is another aspect of reliability. Failure of the sensor to actuate restraints because of failure to detect the collision must be rare. That is, it must successfully detect most of the impending crashes for which restraints are likely to be needed, and in a manner that provides substantially greater protection than non-anticipatory sensors. As a target figure, an actuation reliability of 75% to 90% appears to be a reasonable technical goal; however a rate so far below 100% raises some difficult questions of legal liability.

b. Freedom from Inadvertent Actuation. This specification is inherently dependent on the restraint system in use. Restraints which can readily and economically be refitted, and for which deployment is neither alarming nor physically hazardous to occupants, may allow a false alarm rate which is fairly high. On the other hand, the attitude of the public toward present inflatable systems suggests that much more rigorous standards will apply until these more ideal restraints can be developed. Since this constraint is related not only to technical considerations, but also depends upon public acceptability and mass psychology, no definite specification can be asserted. However, it is clear that performance of a very high order is required.

c. Insensitivity to Environment. The automotive environment is a very challenging one. Temperatures to which electronic components may be exposed range from -40 F to over +200 F; operation must be relatively unaffected by such variation. High humidity and even frequent water immersion must be anticipated. Ice, snow, grease, oil, mud, and other foreign matter may be expected to accumulate in almost any location. Vibration will often be substantial and occasionally severe. The electrical environment can pose a severe problem, as well. Depending on the state of the vehicle's electrical system, available operating voltage can fluctuate from approximately 10 to 16 volts. Automobile ignition systems typically generate severe transients, and other electrical and electronic components, each a possible source of interference, are used increasingly in modern cars.

There is also the problem of external electrical noise. Highways often pass close to radio and television transmitting facilities which may be radiating signals of high intensity. Radar signals in the vicinity of airports can also be strong. These are only a few of the many sources of electromagnetic interference now prevalent in our modern environment. Depending on the nature of the sensor, many other varieties of environmental interference are possible. A careful study is necessary in each case.

Additionally, the prospect of simultaneous use of many crash sensors of a specific type raises the prospect of inter-vehicle interference, triggering of restraints in one vehicle by some aspect of the sensor in a nearby car. Again, this problem must be analyzed in terms of specific system concepts and realization, and may be a real limitation upon any kind of radiating system.

Finally, the "automotive environment" includes the myriad minor dents and scrapes which most vehicles suffer through low speed collisons and parking. The sensor components must be able to survive such hazards with a low probability of either incapacitation or actuation.

d. Resistance to Vandalism. It is an unhappy fact of modern life that vandalism, malicious mischief occurs quite often under many circumstances. It is possible and perhaps even probable that triggering of dynamic restraints will be seen by many as spectacular, frightening, annoying, and generally noninjurious. These are characteristics which could lead to a substantial vandalism problem should such false triggering be readily accomplished by those so inclined, even if the vandal must exercise considerable ingenuity. Once again, the particular nature of the threat depends on system details, but presentation of a false target - one which the sensor will identify as an incipient serious collision but which in fact should be ignored - is a problem likely to be faced by virtually all anticipatory sensor concepts. A system which met all other criteria but was subject to frequent malicious inadvertent actuations would probably be deemed not viable for that reason alone.

A secondary potential problem is that of damage to the sensor itself, as often occurs to car radio antennas and windshield wipers. Thus, the sensor must be such that no particularly obvious elements are involved. (This might be thought of as part of the environment problem.)

e. Low Cost. Several considerations make low cost a necessity. First, the expense associated with almost any conceivable dynamic restraint system is likely to be a significant percentage of the total vehicle cost, and any substantial addition may exceed the breaking point of both the industry and the public. Further, on a cost-benefit basis, the improvement in performance of anticipatory sensors with respect to impact sensors must be sufficient to warrant the probable additional cost. As a rough measure of the numbers involved, it can be noted that the annual cost to society associated with frontal impacts in the 30 to 60 MPH range has been estimated at $3 to $6 billion (refs. 1, 2), or $300 to $600 per vehicle manufactured. This, then, is the magnitude of the economic benefit associated with a perfect anticipatory sensor triggering a flawless restraint system in a fully crashworthy vehicle. However, a number of corrections must be applied to determine a reasonable manufactured cost for the sensor alone. For a basic OEM price of C_m, additional costs for installation, test, overhead, and legitimate profits will imply a consumer cost of the order of $4C_m$. Allowance for inspection, maintenance, and amortization of this investment increases the true total expense to the motorist (and thus to society) to approximately $8C_m$. Finally, the actual potential benefit estimate must be reduced to reflect the imperfections one must expect for any real system - perhaps a factor of two. Thus, one finds a benefit/cost ratio of unity if C_m, the OEM anticipatory crash sensor price, is \$20 - \$40. For a truly viable, desirable system, then, \$10 to \$20 must be taken as a target figure. (Intuitive considerations of motorist acceptability also yield a maximum price in this range.)

At the same time, it should be noted that the extremely large production volume associated with the automobile market might provide considerable help. A commonly used guideline is that an order of magnitude increase in volume is accompanied by a halving of price. While this is both very approximate and not subject to unlimited extrapolation, it suggests that increasing volume by 10^7 can reduce cost by a factor of 128 compared to that for a single unit. Extensive analysis and prototype development is necessary to determine whether even the most promising system will have acceptable cost.

2.2 TECHNICAL REQUIREMENTS

The above listing of necessary system characteristics provides very general guidelines to overall sensor operation. In addition, it is possible to list certain technical parameters, with the understanding that they not be thought of as rigid specifications, but rather be taken as reasonable starting points, to be modified as necessary to accommodate various kinds of passive restraints and vehicle design.

a. Range. As indicated above, actuation approximately 25 msec. prior to impact will permit full deployment of present restraints by impact. At 30 mph this requires 12 inches, and at 60 mph, 25 inches; thus, 2 to 3 feet appears to be adequate. Of course, there are some definite benefits to greater warning. Slower restraint deployment can reduce noise and other hazards, and would increase the degree to which oddly positioned occupants could be accommodated. On the other hand, greater anticipation distance raises the problem of near misses. Considerable variation of trajectory can occur in the last 10 to 20 feet before collision, particularly if the target object is also a moving vehicle. For example, consider the case of two cars approaching each other at equal velocity, both with perfect brakes ($a_p = -1.0G$). If both cars apply full braking power at 15 feet separation with initial closing velocity of 30 mph, they will not collide. For an initial closing speed of 24 mph, impact is avoided if full braking is instituted when the vehicles are only ten feet apart.

Thus, a sensor which attempts to detect impending collisions at such distances must inevitably fail by producing an inadvertent actuation, in a case such as described above, and will be greatly challenged by a wide variety of situations in which accidents are narrowly averted through evasive maneuvers. Even a fairly sophisticated system for sensing target size, shape, position, velocity, and acceleration, and capable of trajectory prediction, will have a difficult task; development of such a sensor, to say nothing of manufacturing it within reasonable cost constraints, seems almost unthinkable. Finally, the technical characteristics of various particular schemes may militate against any attempt to achieve large anticipation distances.

b. Sensing Region. The preceding consideration can be generalized to the question of sensing volume, rather than distance alone. This is closely tied to the nature of the restraints. If no protection is provided in side collisions or rollovers, there is no benefit to sensing them. Moreover, the greater the attempt to sense in other regions than directly ahead of the vehicle, the more difficult the task of eliminating false targets and near-miss situations. On the other hand many collisions which are not purely frontal still have major forward deceleration components for which deployment is appropriate. Restraint effectiveness is enhanced to the degree that such collisions are anticipated. As with many other aspects, this question must be resolved separately for each sensing concept, in the context of actual accident statistics. (The present NHTSA regulations require basic crashworthiness for impacts $\pm$ 30° from frontal; this seems a reasonable general value.)

Additionally, there is the question of vertical range. It is desirable to ignore low obstacles, such as curbs, small ditches, and railroad tracks. At the same time, some large truck bodies overhang the chassis by several feet at a significant height, and an effective sensor should detect such obstacles. A sensing region reaching vertically from approximately one to five feet elevation should be nearly optimal.

c. Velocity. The minimum closing rate for which activation should occur is partially a function of vehicle size, static restraints, etc. It would be desirable also to make this parameter dependent on the nature of the target, but this is probably not feasible. It is a difficult task (perhaps impossible within the indicated constraints) to devise a sensor with satisfactory target discrimination. To attempt to go beyond that is worth consideration but unlikely to be fruitful.

The more important consideration here is to avoid certain types of inadvertent actuations, those associated minor collisions, traffic congestion, parking, etc. Thus, a simple and probably effective approach is to set a threshold speed below which actuation is not permitted. Values typically suggested are 10 to 15 mph.

Note that this raises the question of relative versus absolute velocity. Since the energy interchange in any collision is determined by relative velocity (closing rate), this seems by far the more desirable approach. Consider the case of a vehicle with a speed of 60 mph colliding from the rear with another travelling at 55 mph in the same direction. Deployment is neither necessary nor desirable. Further, if one wishes to use vehicle velocity (ground speed) as a control input, there is a definite instrumentation problem. Collisions can occur under a great variety of circumstances: wheels locked, engine stalled, etc; no simple means is apparent for utilizing speedometer or similar information. (This is not to say that there are not definite advantages to rendering any system inoperative for very low vehicle velocities. Whether this warrants the added complexity and cost depends on the particular sensor.)

There is no upper velocity limit for sensor operation, but proposed crashworthiness regulations require effective triggering to at least 30 mph (barrier crash), equivalent (in some senses) to a 60 mph closing rate with a vehicle of similar size. Effectiveness at higher speeds would be beneficial, and will almost certainly ultimately be required (to the degree that technology permits) up to possibly 50 mph for barrier crashes.

Since system complexity is likely to be related to the span of velocities over which the system must operate, it is desirable to limit response to a maximum of 150 to 160 mph. Such limitation can help in various respects such as noise, false alarms, and intervehicle interference.

Finally, it may be feasible to relate anticipation directly to velocity, so that the time interval t_d used is varied for optimum results. For example, a sensing distance of three feet provides approximately 36 msec. for deployment at 60 mph (about the right amount). But over 100 msec. is provided at 20 mph, leading to deployment 70 msec. in advance of impact; this is not optimal. Sensors which inherently determine velocity, such as doppler systems can permit necessary adjustments with a minimum of additional signal processing.

With particular reference to doppler systems, it should be noted that it is not necessary to design a system which distinguishes between the doppler shift of approaching and receding objects (increase or decrease of original frequency). It is rare that a large object is found two to three feet in front of an automobile, travelling away from it with a velocity greater than 15 mph. (This would imply acceleration of well over 2 G).

d. Response to Various Targets. This topic will be treated for specific approaches in succeeding sections, as appropriate. The basic goal is to respond to the mass or immobility of target objects. While this aim cannot be achieved perfectly in general, the degree to which it is approached provides a useful criterion for consideration of various sensor systems. The context, of course, is that of normal automotive usage: statistics provide some guide. For example, slightly under one-half of target objects in automobile accidents are other vehicles. Similarly, abutments, trees, and standard roadside structures represent objects that it is desirable to be able to detect. Indeed, a detailed study of the relative importance in both numbers and accident severity is useful to the evaluation of suitable sensing techniques. However, as will be seen in following sections, the number of potentially viable concepts is so limited, that (beyond determination of reasonable likelihood of effective operation) this subject does not appear to be an appropriate precursor to an investigation of potential sensing methods; rather it should be a part of the final analysis of system effectiveness.

It is frequently suggested that certain techniques, such as radar, could be made more effective if common objects were equipped with either special reflectors or absorbers so that they are more easily identified as either threatening or non-hazardous. While such actions might be beneficial to enhance the effectiveness of any system which has already been found acceptable, it would be a courageous suggestion indeed that the entire highway environment be so coded simply to make a particular anticipatory sensor viable. (It is likely that such an avenue would be blocked on simple cost-effectiveness grounds, to say nothing of practical and political difficulties.)

2.3 POSSIBLE TECHNIQUES FOR ANTICIPATORY SENSING

There are many known or conceivable means of sensing the presence, closing rate, and nature of nearby physical objects. The inherent characteristics of each technique must be evaluated in terms of the wide variety of targets and environmental conditions which can occur, as well as in the light of the guidelines suggested previously. Most methods can be discarded immediately as far as this application is concerned, and there will be no attempt made here to document the failings of those obviously unsuitable. Nor should this treatment be considered definitive; it is possible that innovative scientists and engineers can devise effective sensors by means not mentioned, or utilizing techniques considered here and discarded. However, a practical investigation is necessarily based on choice of the most promising starting point, and a brief but careful survey appears to suffice in this case. Indeed, the real burden is to illustrate that any truly promising methods can be found.

The basic classifications of sensors used here are mechanical, proximity and ranging. Mechanical methods include the use of probes, extendable bumpers, etc. Proximity techniques are here defined as those which are inherently static, such as capacitive, inductive, magnetic, and radiometric. In ranging sensor systems, as the term will be used here, energy in some form is radiated ahead of the automobile and the reflection (if any) is analyzed by an appropriate detection system to provide information such as range, movement, and size of the reflecting object. All three classes will now be discussed briefly.

2.3.1 Mechanical Systems

Direct mechanical sensing has many advantages. The inertial response of a vehicle in the first stages of a collision gives good discrimination of object mass. False alarms can be virtually eliminated, and properly deisgned mechanical sensors have little sensitivity to environment. They can be inexpensive and their operation can be independent of the surface features and composition of targets. As mentioned previously, mechanical sensors are limited in effectiveness by slow response speed; the collision must start before it can be sensed. Only limited improvement in this respect appears feasible.

There are a number of advanced mechanical techniques that could be explored. The use of a bumper-type probe, suitably styled, that is automatically extended in front of the moving vehicle and retracted at low speeds is one possibility. Undoubtedly a number of innovations are under consideration currently as successors to present mechanical sensors. Further examination of such systems is appropriate, and will be discussed at a later point.

2.3.2 Proximity Systems

Proximity detection techniques are commonly used in many applications. Inductive and magnetic vehicle detection is widespread. However, the apparently inherent flaw in such approaches is the dissimilarity between possible targets. Further, in the unconstrained environment of automobile use, it is difficult, and often impossible to distinguish by such means between effects of range, velocity, and size. Also, electrical techniques (capacitive and inductive) would require physically large sensing structures, which are to prove inconvenient. Another possible proximity detection technique is infrared radiometric sensing. However, this method will probably be far too vulnerable to environment, and is unlikely to be distinguished well between hazardous and innocuous obstacles. In summary, proximity techniques did not appear sufficiently promising to warrant further investigation in this program.

2.3.3 Ranging Systems

2.3.3.1 Optical Techniques - The ease of focusing the transmitted beam and reflected signal at optical wavelengths makes possible excellent discrimination of target position. If a number of transmitted beam paths are used, target dimensions can be measured directly. The closing velocity can be determined from doppler shift or from the rate of change of pulse echo time. At optical frequencies both can be extremely accurate.

An optical system is seriously degraded by dirty apertures, and by dust, fog, or snow in the air. The aperture problem is perhaps not insoluble. But more important, false alarms with an optical system would be extremely difficult to eliminate, due to the fact that heavy snow or fog, or a highly reflective object of low mass, such as a large piece of paper or soft pile of snow, could readily trigger the system. This factor could also represent a substantial vandalism problem.

Although optical equipment possibly could be inexpensive and highly reliable in itself, the environmental sensitivity, susceptability to inadvertent actuation and the possibility of missed target renders optical techniques unsuitable for intensive investigation, regardless of other virtues.

2.3.3.2 Radio Techniques (Radar) - Radar has been developed and used extensively for over 30 years for object detection, most commonly in aviation and marine applications. The basic concept was indicated previously: radio frequency energy is radiated by an antenna, then reflected or scattered by various objects, and received by an antenna that can be the same one used for transmitting. The frequency, transit time, amplitude, phase, azimuth, elevation, and polarization of the received signal all provide information about the reflecting object and its motion relative to the radar system. In particular, by virtue of the familiar doppler effect, the frequency of the reflected signal will differ from that of the transmitted signal by an amount directly proportional to the relative velocity of radar unit and reflecting object. It is electronically simple to mix the received and transmitted energy to obtain an output at the doppler frequency, thus permitting very simple velocity measurement. This technique is called homodyne detection. It is the principle on which police speed-monitoring radar systems operate.

Radar systems can be realized with state-of-the-art components in the frequency range from less than one GHz to tens of GHz (1 GHz = 10^9 Hz). As a general rule, antennas must be of the order of one wavelength wide at the frequency used. For significant directivity, they must be substantially larger. This consideration alone suggests use of a wavelength well under one meter, or a frequency above 300-MHz. Also, targets significantly smaller than one wavelength in linear dimension will not give a useful return.

Another point favoring use of higher frequencies is wider available frequency allocations and reduced commercial use important considerations in avoiding interference.

Further guidance on choice of frequency can be obtained from consideration of available microwave sources. At lower radar frequencies transistor oscillators or transistor-varactor circuits are feasible. However, both represent significant cost and complexity. On the other hand, recent developments in solid state microwave technology suggest the desirability of somewhat higher frequencies. These devices operate particularly well in the range from 10 to 20 GHz, which also permits antennas of convenient size (with apertures of several inches in size).

Still higher frequencies would increase cost substantially, as both oscillatory diodes and other components require much closer tolerances in manufacturing. Commercial and military markets, and hence production volumes, are also much smaller at these higher frequencies. Thus, it appears that the optimum form of ranging system will be microwave radar, in the X-band to K_u-band range.

Whereas range and range rate can be determined directly, the size of the target can generally at best be inferred from the magnitude of the returned signal. One can expect only limited correlation between target mass and measured cross section. Electromagnetic reflectivity is determined by dielectric constant and conductivity. Therefore, reflections from birds, metal cans, scraps of metal foil, sewer gratings, and metal roadways on bridges would compete with returns from dangerous objects such as vehicles, stone walls, trees, and dry embankments.

Pulse techniques offer both advantages and disadvantages. Gating and coding circuits may permit good distance discrimination and high immunity to noise and interference from other vehicles. Information is, in essence, gained over a wide frequency range. On the other hand, complexity and cost is likely to be greater, and antenna size and location may present problems. The viability of such methods is highly dependent on the particular realization considered, but they appear to be no less promising than cw radar.

In summary, microwave radar, while not without serious drawbacks, has in its favor a wealth of well-known techniques and components, and on balance is sufficiently promising to warrant detailed investigation.

2.3.3.3 Acoustic Techniques (Sonar) - The extensive use of sound waves for communication and target detection both in the biological realm and in man-made devices suggests the possible value of an acoustic crash sensor. In underwater applications (fish location, submarine sonar, depth measurement) low frequencies are most often used because of the low attenuation and greater range possible. For an air-medium high resolution system, as the present case, relatively short wavelengths are required - significantly less than one meter; - avoidance of creation of audible noise, as well as low susceptibility to noise, imply frequencies above the audible range: i.e., above 20 kHz. Frequencies above several hundred kHz suffer extreme attenuation in air under certain conditions, and so are unsuitable. Thus, the approximate range of 30 to 100 kHz appears to be the optimum location for an acoustic crash sensor. These are the frequencies used, for example, for sonar aids to the blind.

In the crash sensing application, acoustic ranging or sonar systems have some favorable features. The low propagation velocity permits modulation and signal processing at frequencies approximately one million times lower than for electromagnetic radiation. The reflection time for an acoustic signal from a target at one meter is approximately 6 ms. For simple doppler systems the maximum allowable wavelength for an uncertain ΔR in range and Δv in velocity is given by:

$$\lambda = 4 \ \Delta R \cdot \ \Delta v/V$$

where V is the carrier velocity and v the vehicle velocity. A wavelength λ = 1 cm., corresponding to a frequency of 33 kHz., is allowable in an acoustic system permitting ΔR = 0.1 m. and v = 1 m/sec. (For electromagnetic radiation the same calculation yields a maximum allowable wavelength of 13A.)

In addition, acoustic reflectivity is a function of density and bulk modulus. Therefore, there might be better correlation between mass and echo intensity than there is in the case of electromagnetic signals. Acoustic attenuation in air is much greater than microwave attenuation, and this fact should help limit interference between autos. Because of the longer wave-lengths employed, rain, falling snow, and dust should have less effect on operation of an acoustic system than they would have on an optical system. A specially cleaned window could reduce the effects of the vulnerability of the transducer of antenna apertures to ice, snow, or mud although general environmental problems such as noise wind, road debris, or weather are likely to represent the most challenging aspect of system design. This method appears worthy of further analysis and investigation.

2.4 DETAILED ANALYSIS OF SELECTED TECHNIQUES

The previous sections outlined basic requirements of anticipatory sensors, and indicated some of the difficulties faced in attempting to realize such a system. A number of possible methods have been described, with the conclusion that only three seemed appropriate for further consideration. The three selected were (1) advanced mechanical sensors, (2) microwave radar techniques, and (3) ultrasonic (sonar) systems. A more detailed analysis of these methods follows.

2.4.1 Mechanical Sensors

To obtain advance warning with a mechanical sensor, one must, in essence, advance the physical position of the sensor relative to the automobile. There are a number of difficulties associated with this approach. The key problem with most anticipatory sensing concepts is avoidance of false alarms from the many and varied obstacles or objects a car might conceivably strike. An indication of the mass (or immobility) of such a target is necessary in order to predict the seriousness of the collision, and thus determine whether restraint system deployment is warranted. While a mechanical system offers this capability directly, the sensitivity of this method depends on the capacity of the sensing system to absorb energy. For currently conceived sensors, the sensing system essentially consists of a firewall-mounted accelerometer plus the entire front section of the automobile. If the accelerometer is to register a sustained five-G deceleration, a large amount of energy must be transmitted by the quite massive forward assembly so that an unequivocal crash indication is obtained. On the other hand, a physically small sensor extended in front of the car might undergo severe decelerations even for relatively small impacts. Further, such a sensor protruding from the vehicle would be a safety hazard in its own right, even if withdrawn at low speeds. Finally, a mechanism which could extend and retract a reasonably massive wide sensor strucutre, cycle reliably every time the car passes a set speed, and operate for perhaps ten years without maintenance or failure, would be very difficult to produce at an acceptable price, even in very large quantities. To obtain real benefit, the extension would have to be substantial. At 60 mph, allowing 10-msec for sensing and triggering, and further assuming a 30-msec crush time for the vehicle engine compartment, the sensor would have to impact the target 3 to 4 feet in front of the car.

This is not to say that advanced warning cannot be obtained mechanically. Two aspects of automotive development may contribute to the utility of this method. First, as the design of the forward sections of automobiles are improved with respect to energy absorption, a small but significant decrease may be achieved in the degree of impact anticipation required. Of greater significance is the potential development of extendable, energy-absorbing bumper structures. The principle motivation for such development is energy absorption to minimize damage to the vehicle at low speeds, or to the occupants at higher velocity. However, these characteristics should make it well suited to sensing impact in a manner appropriate for triggering of restraint systems.

Since the viability of a mechanical crash sensor depends so heavily on these other developments currently outside the purview of TSC, there has been no further investigation of this concept.

2.4.2 Guidelines for Analysis of Ranging Systems

Before discussing the microwave and ultrasonic radar systems in detail, it is appropriate to examine inherent characteristics of these different modes. Points which must be included in any serious investigation include:

a. Signal Strength

   1. source
   2. transmitting transducer
   3. path loss
   4. target characteristics
   5. receiving transducer
   6. receiver

b. Environment

   1. variability of propagation
   2. weather protection
   3. noise spectrum
   4. vandalism

c. Overall System Aspects

   1. inter-vehicle interference
   2. radiation hazards
   3. cost

d. Effectiveness

1. "True" collisions
2. "False alarms"

While some of these points require further investigation or evaluation, all can be discussed to some degree for both types of ranging sensors. Cost factors, item c.3., will be discussed under other headings also, as relevant.

2.4.3 Microwave Radar Crash Sensors

2.4.3.1 Signal Strength -

a. Source. Microwave solid state sources have been the subject of intensive investigation, principally sponsored by NASA and DOD, for a number of years. Two types of oscillatory diodes have been realized in practical form, both providing direct conversion from dc to microwave power with no additional circuit elements beyond the diode and its mounting. The avalanche, or IMPATT (Impact Ionization-Avalanche-Transit Time) junction diode is somewhat more highly developed and more efficient than the Gunn (transferred electron bulk-effect) diode, but requires approximately 80 volts for a 10-GHz diode, compared to the convenient 12 vdc for the latter. Costs and reliability are about equal. Either could be used in an automotive system, but the necessity of compatibility with battery operation, initially favors the Gunn device. (Use of the IMPATT would require a dc to dc inverter circuit, and a slight but possibly significant increase in cost. Diode cost and reliability will utlimately determine the choice.) While these devices are currently quite expensive, one manufacturer has publicly announced plans to market Gunn diodes at $5 each in lots of 100,000. The history of the semiconductor industry, and its economic dynamics, are such that one can quite confidently predict even lower prices should a large-volume market develop. (Transistors, for example, once very expensive, now often sell for a few cents in unit quantities, and a fraction of a cent in large volume.)

Power output of 100 mW is easily obtained, and is more than is necessary for this application. Reliability is estimated to be greater than 40,000 hours mean operating time before failure. This estimate largely represents the limited time such tests have been underway; 100,000 hours is quite possible.

b. Transmitting Antenna. Two types of antennas seem appropriate to this application. One, the familiar horn type, could easily be cast, molded, etc. It seems unlikely that such a simple unit could cost significantly more than the material from which it is fabricated when used in automotive quantities. An alternative, not yet developed for civilian use, is the planar array of slots or dipoles, with either stripline or waveguide feed. It can be more compact and lower in cost than the conventional horn when produced in high volume. It also offers somewhat greater ease of controlling antenna pattern. Both types have bandwidths of at least tens of megahertz.

c. Path Loss. Air, even under extreme weather conditions, has negligible microwave attenuation for such applications. At 10 GHz, the cloudburst-intensity rain, attenuation may reach 20 dB/kilometer, or .02 dB/meter.

d. Target Characteristics. Targets can be of wide variety, both reflective and scattering. The waves will be reflected or scattered by obstacles or portions of obstacles comparable in size to a wavelength -- 3 cm at 10 GHz.

Generally, good reflection will depend on the dieelectric properties and conductivity of the target surface. Hence, there should be substantial reflection and scattering from motor vehicles, no matter what the aspect. Dry telephone poles, on the other hand, may give a small return, and large wet animals would reflect quite well. Concrete, brick, and stone should be good reflectors.

e. Receiving Antenna. Microwave antennas are typically of wide bandwidth and highly efficient. Receiving and transmitting antennas can be identical if desired.

f. Receiver. For reasonably simple signal processing, as is envisioned, a very few components -- diodes, integrated circuits, etc. -- are needed. Cost, in high volume, can be very low, with no compromise in reliability.

2.4.3.2 Environment -

a. Variability of Propagation. As indicated above, microwave propagation over such short distances is essentially unaffected by temperature, humidity, or precipitation.

b. Weather Protection. Due to widespread usage of microwave communication systems, the state-of-the-art in weather proofing is highly advanced. In addition, the transparency of many materials to electromagnetic radiation makes this a relatively easy problem.

Antenna covers ("windows") with appropriate dielectric constant and conductivity have very little effect on transmission, and cost very little for small antennas.

c. Noise. Both man-made and natural background noise are reasonably low in the microwave range. It should be possible to design a practical crash sensing system that is activated only by signals much stronger than prevailing noise levels.

d. Vandalism. The principal concern here is with maliciously induced restraint deployment. As indicated previously, a false microwave signal would be very unlikely to fall in the passband of the receiver. (Even a swept frequency system would be unlikely to fall in the passband sufficiently long to induce triggering.) This, coupled with the absence of microwave sources from the public market, should prevent any serious problems from extraneous signals.

The far greater difficulty lies with creation of false targets. This is closely related to the general false-alarm problem, and the same treatment serves for both. Basically, this must consist of use of a high triggering threshold. For example, the system should not trigger for any target, no matter how high its reflectivity, which has a physical area of less than one square foot. With this requirement, it is unlikely that many such objects can be thrown successfully. There is, however, the additional problem that otherwise harmless obstacles might be placed in the road and cause deployment. This could turn out to be either a serious problem or a very minor one; further system development is necessary for such a determination.

While a crash sensor could be rendered inoperable by vandalism to the car, the antennas should be readily integrated into the design -- they need by only 3 to 5 inches in diameter -- and should not attract attention. The weather-proofing shields can be extremely durable. Finally, there should be very little satisfaction to such vandalism; immediate breakage could be barely noticeable, and failure of the system would be exceedingly unlikely to occur in the presence of the miscreant.

2.4.3.3 Overall System Aspects -

a. Intervehicle Interference. Analysis of this aspect requires an estimate of system bandwidth. While sophisticated systems could have very substantial requirements, there is a basic minimum. A simple continuous wave (cw) technique requires at the very least that the receiver be able to accept a frequency f_r equal to the transmitted frequency f_o plus any foreseeable doppler shift f_d:

$$f_r = f_o + f_d$$

In general, $f_d = 89.6 \times v_{mph}/\lambda_{cm}$,

where v_{mph} is the closing rate in miles-per-hour, and λ_{cm} is the wavelength of the radiated signal in centimeters. (These mixed units are convenient in this application.)

Since $f_o = c/\lambda_{cm}$, with c the propagation velocity in cm/sec.,

$f_d = [89.6 \times f_o/c]\ v_{mph}$, or

$$\frac{f_d}{f_o} = \frac{89.6}{c} v_{mph} = .3 \times 10^{-8} \times v_{mph}.$$

To allow for closing rates of up to 160-mph, the maximum f_d/f_o which the system must accept is

$$\frac{f_d}{f_o} = .5 \times 10^{-6}$$

This not only establishes the extremely narrow-band nature of the system, but also shows that for $f_o = 10$ GHz, the maximum $f_o = 5000$ Hz. Thus, if a .5 GHz band is available for crash sensors, centered near 10 GHz, 100,000 transmitters could coexist with no interference. Probability theory shows that a specific car could be brought into close frontal contact with 69,000 other radar-equipped vehicles, with a 0.5 probability of at least one inadvertent triggering. Expansion to a 2-GHz band, and reduction to 100-mph (and lower) closing rates would increase this to over 346,000 exposures to other crash-sensor transmitters before a 0.5 probability was reached. If the transmitting antenna is on the left side of all vehicles, this should greatly reduce the number of such exposures, since all autos will radiate their microwave beam toward the roadside. Remaining occurrences typically would involve cars at right angles, as in intersections. If the system were inoperative at extremely low vehicle velocity, this problem would be further relieved. Only actual tests can show how close two vehicles would have to be to bring about triggering, but the broad antenna patterns typically used should provide enough spreading loss after a fairly moderate distance.

This is clearly a problem area so far as widespread use of a microwave system is concerned. On the other hand, the above discussion is intended to indicate that it should not be an insurmountable one, simply on a statistical basis. Beyond that, one could go to coding schemes in which a given receiver can "recognize" signals of that vehicle's transmitter.

b. Radiation Hazards. For antennas of modest directivity, as planned for the sensor, with a 100 mW oscillator, power density at the antenna is approximately 1 mW/cm^2, an acceptable level. (The present voluntary U.S. standard is 10 mW/cm^2, averaged over any six-minute period. Current HEW requirements for microwave ovens, recently made more stringent, permit 1 mW/cm^2 new; 5 mW/cm^2 over the life of the unit. FCC limits on intrusion alarm systems are of this order.) An operating system may well require substantially less power than the 100 mW indicated, so that a radiated power density of .1 mW/cm^2 is feasible. Again, if the system is inoperative at zero and very low speeds, individual exposure can be very low.

c. Cost. Cost factors were considered to some degree in Section 1; at present, it appears that a microwave sensor system could be produced for \$10-\$20. However, solution of some of the possible problem areas indicated (or others as yet hidden) could bring about a drastic increase.

d. Effectiveness. The ultimate system effectiveness of a microwave crash sensor cannot yet be determined. More than half of the fatal collisions involve impact with another vehicle, which will presumably be a good radar target. The distribution of other targets, and evaluation of system effectiveness for them, awaits both experimental tests and further study of accident statistics. (Verification of the radar characteristics of automobiles is also needed.)

Rejection of virtually all false alarms remains a difficult problem, but should be possible by imposing a sufficiently restrictive test for triggering, such as a high amplitude threshold for the reflected signal. On the other hand, this will reduce the probability of deployment in a "true" collision. Again, experimental data is required.

2.4.4 Ultrasonic Sonar Crash Sensors

2.4.4.1 Signal Strength -

a. Source. There should be no difficulty in design of a reliable, low-cost transistor oscillator using integrated circuits. Consumed power should be of the order of watts at most, and should be easily supplied by an automobile electrical system.

b. Transmitting Transducer. For a cw (continuous wave) system, a narrow-band transmitting transducer is sufficient, provided that the oscillator is adequately stable. Reasonable efficiency is desirable, to minimize the power required from the oscillator circuit. For a system involving sophisticated modulation -- coding, chirp, etc. - bandwidth could be a problem, as indicated earlier. Radiation pattern should be readily tailored to the desired shape.

c. Path Loss. Atmospheric attenuation of acoustic waves is strongly dependent on temperature, humidity, and frequency. Under the best conditions, even at 100 KHz, the loss can be under .1 dB/meter, which would be negligible in this application. However, the worst case can reach 10 dB/meter, or for a total path length of 3 meters, 30 dB loss. (This is for 100 KHz; attenuation is proportional to the square of the frequency.) While loss of this magnitude can be made acceptable through use of increased transmitter power, the consequences of variation from low to very high attenuation due to changes in environment are far more serious.

d. Target Characteristics. As for the microwave case, the ratio of wavelength to target dimension is a crucial parameter. Acoustic wavelengths for a reasonable system would be in the range from 1.5 to 0.3 cm about one-half to one-tenth of those for a 10-GHz microwave system. Thus, a high degree of spatial resolution would be obtained. However, for a crash sensor it is not clear that a resolution of less than 5 to 10 cm is needed. Whether this aspect is of particular value depends on whether one can devise means to utilize the added information.

The important question here concerns the reflection coefficients of the various obstacles to which the system is likely to be exposed. For acoustic waves, this coefficient is a function of bulk modulus and density. Thus, it seems reasonable to anticipate some correlation with mass (probably better than for microwaves), which is highly desirable. Absorption, as in the case of fur on an animal or a hedge, might aid in reduction of false alarms. Indeed, these considerations are the basic reason for examination of ultrasonic systems. Experimental tests are necessary, of course, to confirm or refute these estimates. On the other hand, objects made of cardboard, wood, glass, etc., may also give rise to a large reflection, presenting a special false alarm problem.

e. Receiving Transducer. Regardless of the sensing method used - whether pulsed, coded, or cw - the bandwidth requirement will be at least that of a cw doppler system for equivalent information. Recall from part 3.4.3.a. that for the microwave system,

$$\frac{f_d}{f_o} = \frac{89.6}{c} \times v_{mph}$$

For sound, c = 33,100 cm/sec.; therefore,

$$\frac{f_d}{f_o} = .0027 \; v_{mph}$$

So to provide for even a 125-mph closing rate, we must have

$$\frac{f_d}{f_o} = .35 = 35\%$$

In other words, the receiving transducer and the entire receiving system must have a 35% bandwidth, with a center frequency between 20 and 100 KHz, and a relatively flat response in this range. While this can presumably be obtained, the cost remains to be determined. This question is still open. In addition, the problem of retaining such characteristics when the transducer is completely protected against weather extremes is a very severe challenge since resonant structures are generally part of any such shielding.

f. Receiver. Basic receiver circuitry should pose no major difficulty, although the greater the degree of sophistication in modulation, the greater the cost of demodulation and transmitter circuitry.

2.4.4.2 Environment -

a. Variability of Propagation. This is a factor which must be considered. As indicated above, atmospheric attenuation at 100 KHz can vary from less than 1 dB/meter to approximately 10 dB/meter; for a 3 meter path, varying conditions can cause received signals from a given target to shift by 30 dB, a factor of 1000 in signal strength. If not compensated, this would completely rule out any use of amplitude measurements for triggering decisions. This suggests operation at much lower frequencies, 30 to 50 KHz. However, this will enhance noise problems, and may still leave a 6-dB variability in return signal level.

b. Weather Protection. Protection of acoustic transducers against weather extremes presents clear difficulties. It is not difficult to obtain an hermetic seal, but typically this is accomplished by means of a resonant window which has a narrow bandwidth. Since high frequency operation inherently requires moving parts of low mass, ice buildup on the front surface could completely destroy its transduction properties at the design frequency. In addition, this low mass of moving parts, ice buildup on the front surface could completely destroy its transduction properties at the design frequency. In addition, this low mass is basically inconsistent with the structural strength required to survive sleet and hail, along with other objects such as sand, gravel, etc.

c. Noise Level. At present, this is an unknown quantity. Measurements of enviornmental noise are generally limited to the audible range, below 20 KHz. However, some informed speculation is reasonable. A commercially developed system for passive detection of automobiles operates at 40 KHz, where tire and other noise is apparently very high; motorcycles a hundred feet away have been found to produce a very high sound level at this frequency. As there is little likelihood that such noise is sharply peaked in frequency, it is reasonable to assume that the range between 20 and 100 KHz may be quite noisy. In addition to normal road noises, there are other common sources such as backfiring, explosions of any sort, thunder cracks, construction, manufacturing (generally close to highways, and almost certainly in the vicinity of parking lots) and the squeal of sudden brake applications in panic situations. It is extremely likely that the noise of a low-flying jet aircraft, particularly when taking off, contains very high intensity components over the entire range of interest.

A second possible noise source is air turbulence in the propagation path. In addition to normal wind flow and self-generated turbulence, air movements caused by nearby vehicles, such as large trucks in an adjacent lane, can severly affect an acoustic wave passing through that medium. The turbulence can have dimensions over which there is a pronounced change in velocity, direction, or density, either larger than, comparable to, or smaller than the acoustic wavelength in use. Therefore, a wide variety of effects can occur, including scattering, reflection, diffraction, and refraction. All of these will tend to add noise to the received signal and to introduce random variation into it. Indeed, this effect has been reported as experimentally observed at audio frequencies, and apparently increases as the square of the frequency. Thus, the effect of turbulence also seems to be a serious problem for acoustic systems.

A related noise source is rain or spray, where dimensions could conceivably be such as to approach signal wavelength; however, this factor should be considerably less important than turbulence. More serious is physical impact on the transducer by rain, sleet, sand, or pebbles. This will certainly introduce high-intensity noise components into the receiver; the resulting effect on system effectiveness remains to be evaluated, but is clearly an area requiring study.

In short, further investigation is required for a definitive answer on all of these questions. However, noise does appear to be a very real problem for any ultrasonic system to be used in an automotive environment. It may be insoluble within reasonable cost and other constraints.

d. Vandalism. For an acoustic system, there are two facets to this problem. Not only can objects be so placed or thrown as to cause undesired deployment; triggering can also be achieved from use of an appropriate signal source, such as an ultrasonic whistle (perhaps a "silent" dog whistle) or a small firecracker, likely to generate substantial ultrasonic components. "False alarm" targets might be successfully excluded through use of a sufficiently high triggering threshold, but the false signal source may be impossible to defend against without going to considerable costly sophisitication in signal processing.

2.4.4.3 Overall System Aspects -

a. Inter-vehicle Interference. As indicated previously, an acoustic crash sensor will require a very broad bandwidth -- at least 30%. Further, propagation characteristics and other factors limit choice of frequencies to a small range -- above 20 KHz and probably below 100 KHz. Hence there are far fewer independent channels than in the microwave case, and one must assume that essentially all units can interfere with one another. Although atmospheric attenuation can be very high, it can also be quite low, and can not give useful protection from nearby sonar-equipped cars. It appears that some sort of coding scheme will be necessary so that the receiver will respond only to signals that it has transmitted. This will add an unfortunate degree of complexity and cost to ultrasonic anticipatory systems if it can be accomplished at all; only a limited amount of coding is possible in the time intervals involved for the frequency range in question.

b. Radiation Hazards. For the acoustic power levels planned, no radiation hazard should exist. Only enough return signal is required, after traversing a very short path, to be above the ambient noise level. On the other hand, an attempt to eliminate "false alarms" associated with special noise sources (jet planes or thunder claps, for example) by setting a very high threshold might lead to use of such intense pulses that consideration would have to be given to this factor. (It has not yet been determined whether permissible levels in the audible range are valid standards for ultrasonic energy. This information can possibly be obtained from the medical literature.)

c. Cost. A basic system need not be excessively expensive. But to overcome all the actual weaknesses and problems discussed here might be costly.

d. Effectiveness. A single, basic ultrasonic crash sensor, under given conditions, might well provide a good predictor of impending collisions, with acceptable reliability but rather poor discrimination against false alarms. In addition, the probable susceptability to atmospheric variations, general environment, ambient noise, and acoustic false alarms -- due to sounds, not actual objects -- make this a relatively unpromising path to follow.

2.4.5 Conclusions

As indicated, the constraints and difficulties associated with mechanical anticipatory sensing made it inappropriate to continue the TSC investigation along these lines.

While not without substantial problem areas, microwave sinsing is found to hold the greatest promise for this difficult application. Since many of the uncertainities can be resolved only through the attempt to construct a working sensor, and by careful test and evaluation of such a system, this has been the course followed. The sensor actually developed is described in the following chapter.

Although acoustic techniques are substantially less likely to lead to a viable crash sensor, the above comments concerning the value of fabrication and test of an actual unit are also valid for that approach. In addition, in the course of this program, the microwave radar system developed at TSC was seen to be based on a system concept for which completely analogous acoustic realization is possible. Indeed, the same signal processing circuit can be used for both microwave and acoustic sensors with only very minor parameter changes. Thus, it has been seen as appropriate to devote a significant amount of effort to the sonar approach as well. This study is also described in the following sections.

3. CRASH SENSOR REALIZATION

3.1 RADAR

The analysis contained in the preceding chapter leads to the conclusion that a microwave radar approach offers the most promise of success in the quest for a viable anticipatory crash sensor. Many of the basic design constraints and specifications have been established. It is now necessary to discuss the form such a system might take.

The most common types of radar in which target range is of interest are pulsed systems, in which the time interval between transmission of a burst of electromagnetic energy and the reception of its reflection gives the range. A target at a range R produces a return t seconds later, where $t = 2R/c$, c being the velocity of light. For R = 300 kilometers, t = .002 sec = 2 msec. However, for the radar application considered here, the problem is more severe. For a target one meter from the antenna, the reflected signal returns in 6.7×10^{-9} sec = 6.7 nsec. Resolution of better than a nanosecond would be necessary if one wished reasonable accuracy, implying bandwidths of several gigahertz. In addition, fundamental constraints on the precision with which range and closing rate can be measured simultaneously raise difficulties.

The generation, reception, and processing of very short pulses is a complex subject, which will not be treated here. These problems can be solved, and - indeed - a prototype short-pulse anticipatory sensor has been constructed.[3] Further, if one is prepared to enter into the complex realm of target signature analysis, the inherently wideband return from a pulse of brief duration carries considerable information. (The situation is analogous to characterization of a system by its impulse response.)

An alternative to this technique arises from noting that ranging information is not inherently required; one merely needs to know whether there is a target (larger than a specified size) within a certain volume. If the radar is sensitive only to properly located obstacles, a particularly simple CW (continuous wave) system is possible in which closing rate can readily be measured through the doppler effect. It is such an approach that has been followed in this program.

This choice is based upon simplicity (presumably correlated with low cost and high reliability) of system realization, availability of existing technology, and the generality of information which can be obtained. This is not to deny, however, that short-pulse radar also represents a highly developed, if more complex, technology, which may be quite appropriate to this application. The basic CW radar which forms the focus of this study is intended to serve as a baseline, chosen as both a promising concept and a means of illustrating and illuminating the general strengths, weaknesses, cost, reliability, and other characteristics likely to be common to practical anticipatory sensors. It is appropriate to note that a similar conclusion has been reached by other researchers.[4,5]

3.1.1 A Radar Crash Sensor

The crash sensor to be described is a bistatic CW homodyne doppler radar. The term bistatic means that separate transmitting and receiving antennas are used. Position discrimination is accomplished simply through overlap of the antenna patterns, so that no sxplicit modulation is required - it is a continuous wave (CW) system. Frequency modulation (doppler shift) of the received signal, as a result of movement of a reflecting object in the overlap region, is detected by a simple mixer which utilizes a sample of the transmitted signal for local oscillator power (homodyne operation). This chapter will be directed primarily at detailed analysis of this basic approach and relevant variations.

3.1.2 Characteristics of Bistatic Systems

3.1.2.1 Introduction - Bistatic systems are widely used in various applications for a number of reasons. Often the object is merely isolation between receiver and transmitter. However, for the anticipatory crash sensor the two-antenna arrangement is fundamental to the position discrimination function. No "ranging", per se, is required; it is merely necessary to determine that a reflecting object is or is not within a reasonably specific zone in front of the vehicle. This is illustrated in conceptual form in Figure 3-1 a. Some additional benefits are obtained. For example, there is no danger that a small, very close target could give the same effect as a large object at a greater distance. (See Figure 3-2.)

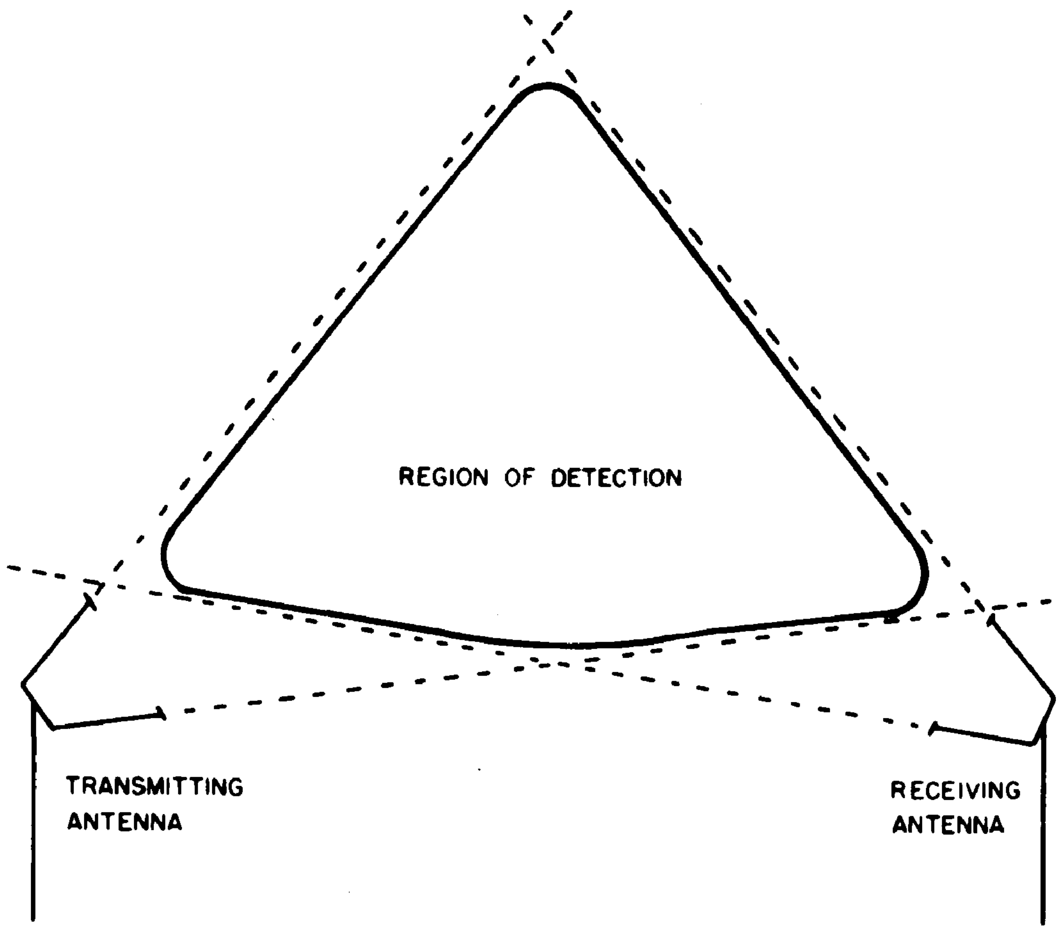
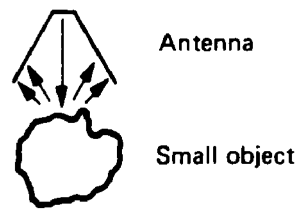
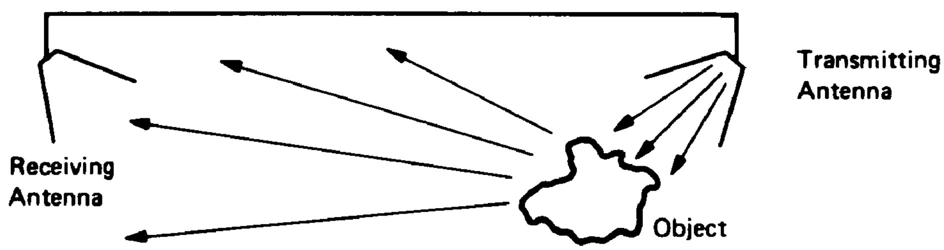


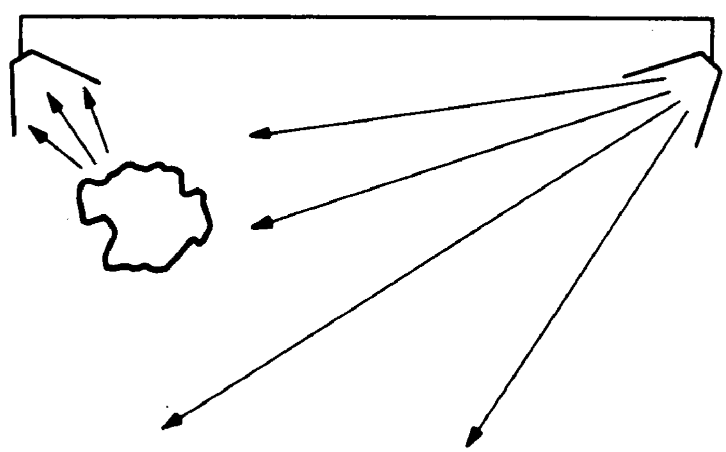
Figure 3-1 Basic Bistatic Antenna Configuration and Region of Sensitivity



(a) Single Antenna. Large reflected signal received by antenna.



(b) Two Antennas. Only small portion of large reflected signal is incident on receiving antenna.



(c) Two Antennas. Only small reflected signal; very little of transmitted energy incident on object.

Figure 3-2 Insensitivity of Bistatic System to Small, Nearby Objects

3.1.2.2 The Doppler Effect - The classical doppler effect relates to the difference between the frequency of a signal as measured at the source and as measured at a receiver moving toward or away from the source. For example, the horn of an approaching automobile sounds higher in pitch to a stationary observer than to the occupants of the car; and the light of the stars moving rapidly away from the earth appears lower in frequency (redder) than would be perceived at the star (or fron a point not in motion relative to the star). The situation is somewhat different for a radar system, although the results are equivalent. In a CW homodyne system, the source transmits a continuous sinusoidal wave, a sample of which is simultaneously applied--along with the received (reflected) signal -- to a mixer. This component, by definition, provides an output at a frequency equal to the difference between the frequencies of any two signals applied to it.

For a transmitted signal of the form $e(t) = E_o \sin\omega t$, traversing a distance d_t from transmitter to reflecting object, and a distance d_r from target to receiver, the received signal will be of the form

$$e_r(t) = E_r \sin(\omega t - \frac{\omega}{c} d_r - \frac{\omega}{c} d_t),$$

where c = wave propagation velocity, and E_r is the received amplitude, a function of d_t, d_r, and the target characteristics.

In terms of the total path length $\ell = d_t + d_r$,

$$e_r(t) = E_r \sin(\omega t - \omega\frac{\ell}{c}) = E_r \sin(\omega t - \phi_\ell)$$

where ϕ_ℓ may be interpreted as the total phase shift associated with the path ℓ. Note that $\frac{\omega}{c} = \frac{2\pi}{\lambda}$, so $\phi_\ell = 2\pi\frac{\ell}{\lambda}$. Thus, a change in total path by a distance λ represents a phase change (delay) of 2π.

Now consider the case of a target moving at a velocity v_o directly toward a monostatic radar system (same antenna for both transmitting and receiving). Then $d_r = d_t = d_o + v_o t$; $\ell(t) = 2d_o + 2v_o t$, and

$$\phi_\ell = \frac{2\omega d_o}{c} + \frac{2\omega v_o}{c}t = \phi_{\ell_o} + [(\frac{\omega}{c})v_o]t$$

so $e_r(t) = E_r \sin[(\omega - \frac{2\omega v_o}{c})t + \phi_{\ell_o}]$ and the received signal may be considered to have a frequency of $\omega_r = (\omega - \frac{2\omega v_o}{c}) = (1 - \frac{2v_o}{c})$

The mixer, with output at the difference frequency, will thus be at a "doppler" frequency $\omega_d = \omega - (\omega + \frac{2\omega v_o}{c})$ or, in terms of true rather than angular frequency, $f_d = -\frac{2f_o v_o}{c} = -\frac{2\omega v_o}{\lambda}$. For example, with f = 10.5 GHz, $f_d = 31.4$ v Hz, with v in miles per hour. (An unconventional but useful mixing of units.) That is, the frequency of the mixer output is given by $f_d = 31.4$ Hz/MPH. A 30 MPH closing rate implies a doppler frequency of 942 Hz. (The minus sign above merely indicates that motion toward the radar--v_o negative--implies an increase in received frequency -

a positive doppler frequency. However, a simple mixer system, which does not respond to the phase of received signal, cannot distinguish between approaching and receding targets.)

The above treatment is based on a single-antenna system. A bistatic antenna configuration significantly affects the observed doppler frequency, as a function of target position, for constant target velocity. This can be seen as follows. In the above description, one doppler cycle is produced at the mixer as the total path length from transmitting antenna to target to receiving antenna changes by one microwave wavelength (i.e., as λ changes by 2π.) In the bistatic case, d_t and d_r are not, in general, equal, and the loci of points of constant relative phase (i.e., constant total path length) are ellipsoidal surfaces with the antennas as foci; these are illustrated in Figure 3-3a. The effect of this on doppler frequency can be expressed in terms of a function g(r), defined by $f_d = \frac{2fv}{c} g(r)$, where g(r) is the ratio of the actual doppler frequency to the doppler frequency for the monostatic case--that is, far away in comparison to the antenna spacing, but with the same relative direction of motion. A typical diagram of g(r) for a target moving at constant velocity on the system axis directly toward a point midway between the antennas, is shown in Figure 3-3b. This geometric effect causes an ambiguity in determining target velocity from doppler frequency, and must be taken into account in choice of antenna patterns and velocity thresholds. Calculations of this effect have been made for a number of target trajectories. Figures 3-4 to 3-9 include diagrams showing the paths considered (a) and the variation of the

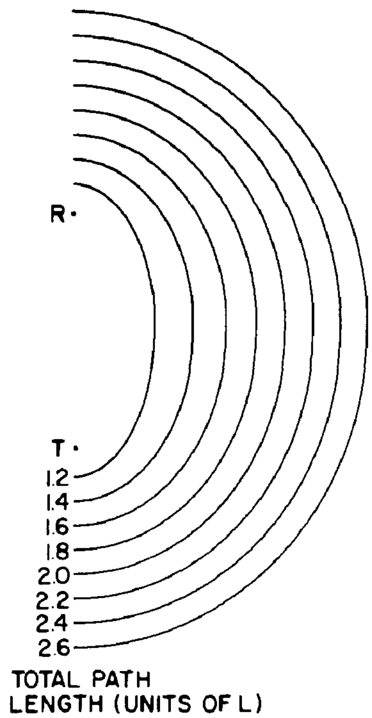


Figure 3-3a Contours of Constant Phase (Path Length) for a Bistatic Configuration with Antenna Separation L

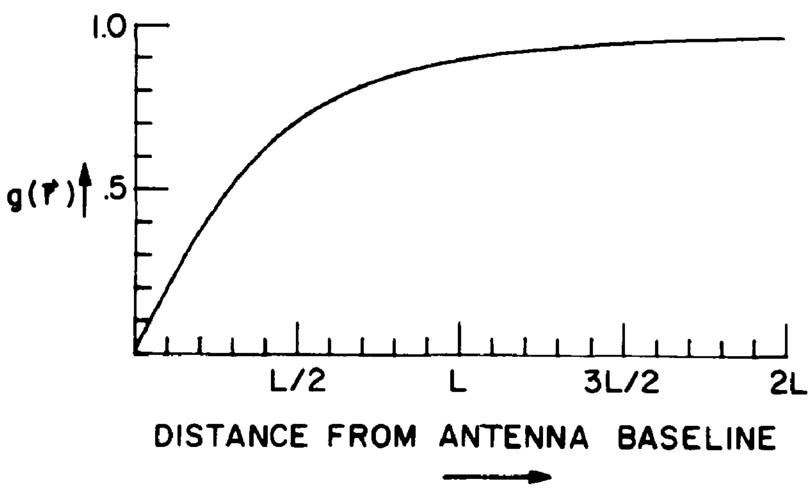
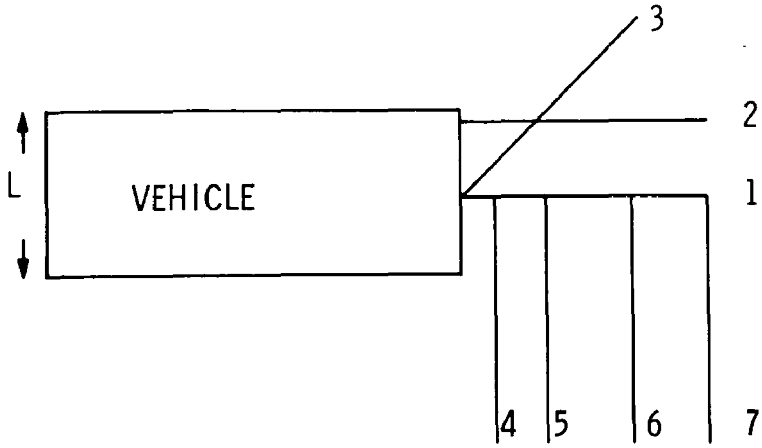
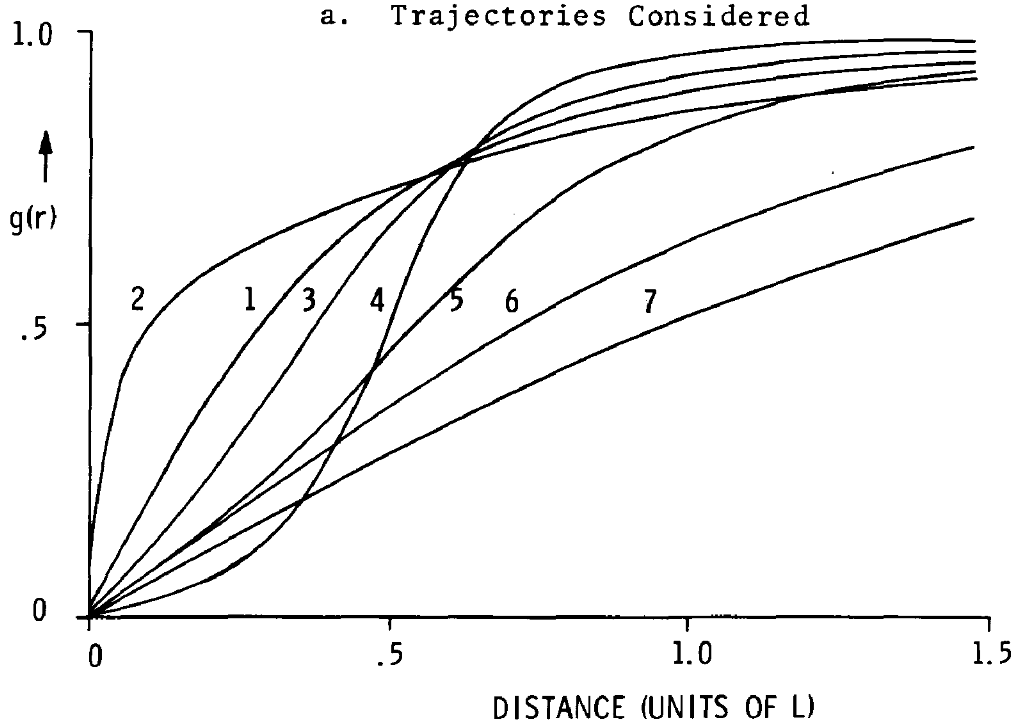


Figure 3-3b Ratio g(r) of Actual Doppler Frequency to that for Target Distance Large Compared to L

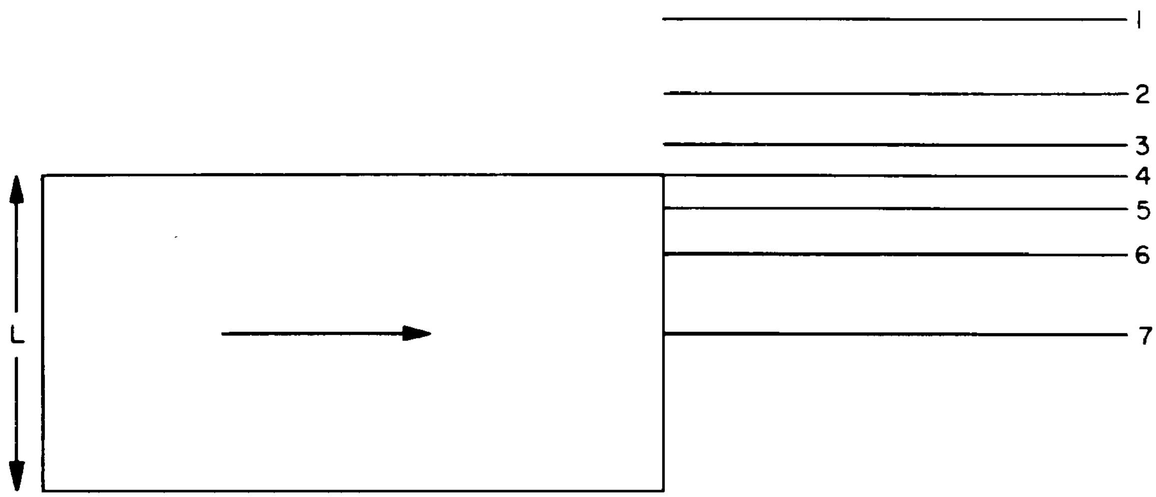


a. Trajectories Considered

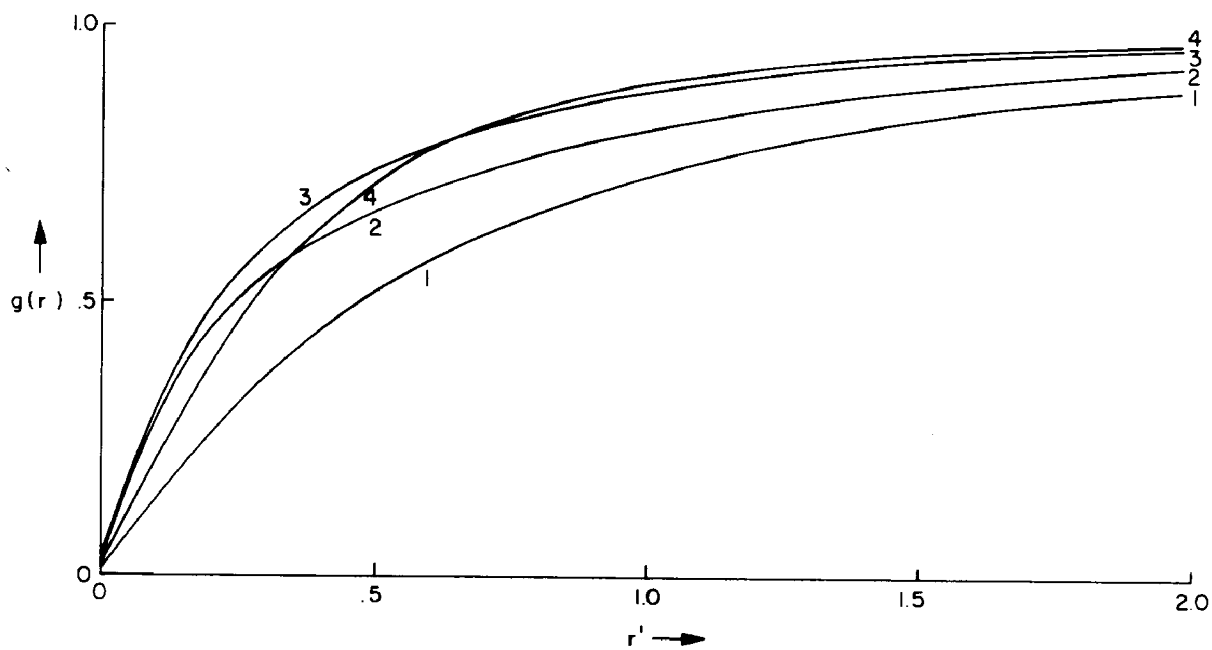


b. Variation of Doppler Frequency

Figure 3-4 Variation of Doppler Frequency with Trajectory (Different Trajectories)

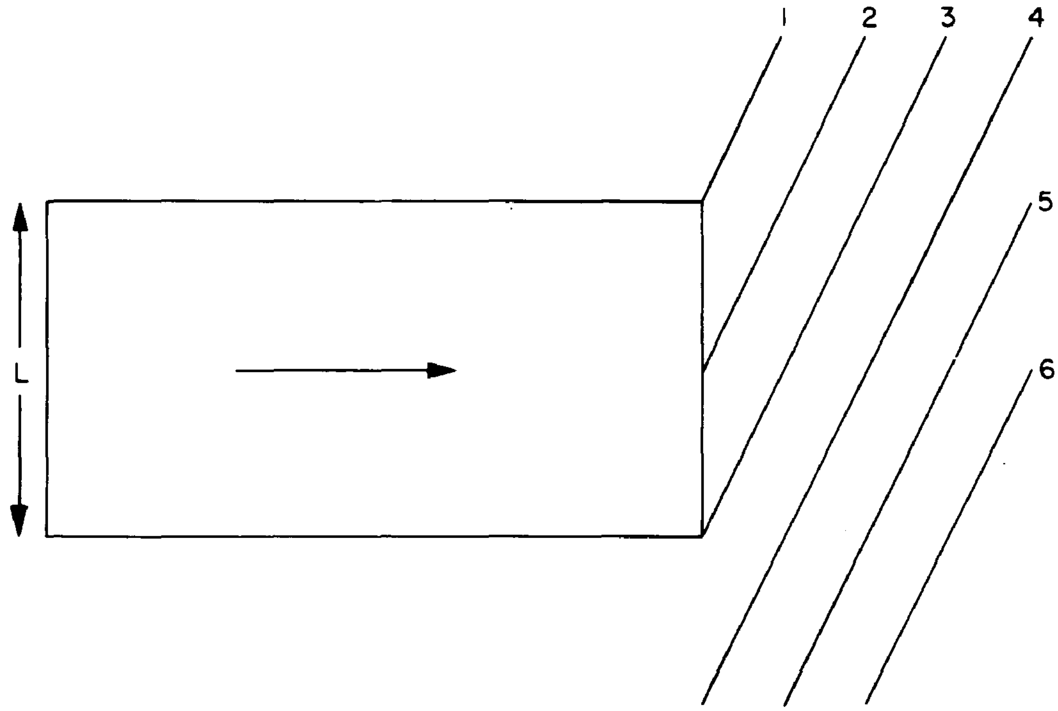


a. Trajectories Considered

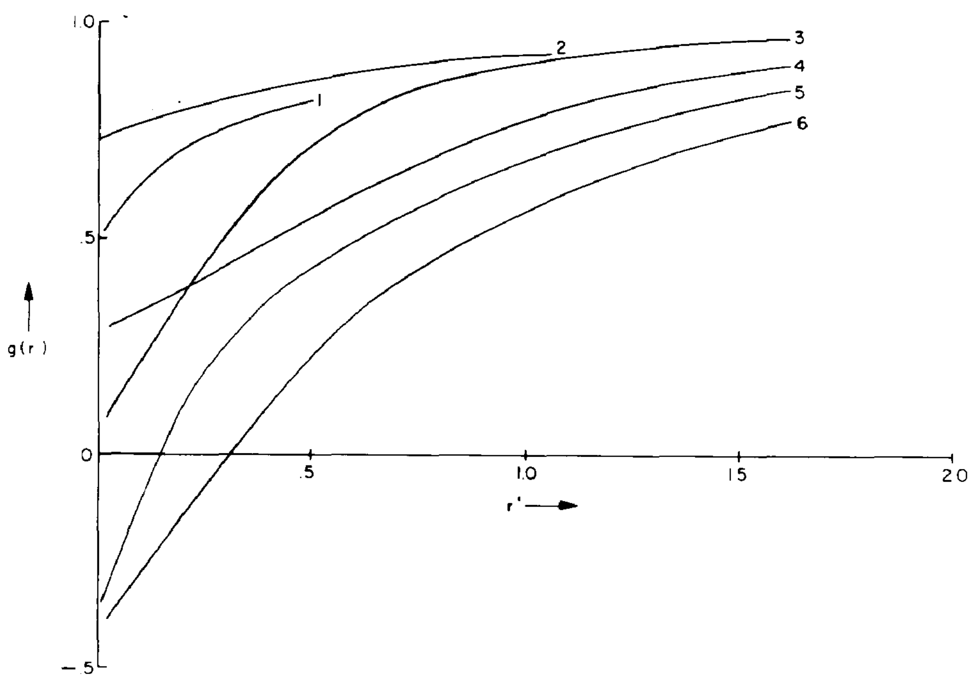


b. Variation of Doppler Frequency

Figure 3-5 Variation of Doppler Frequency with Trajectory (Different Trajectories)

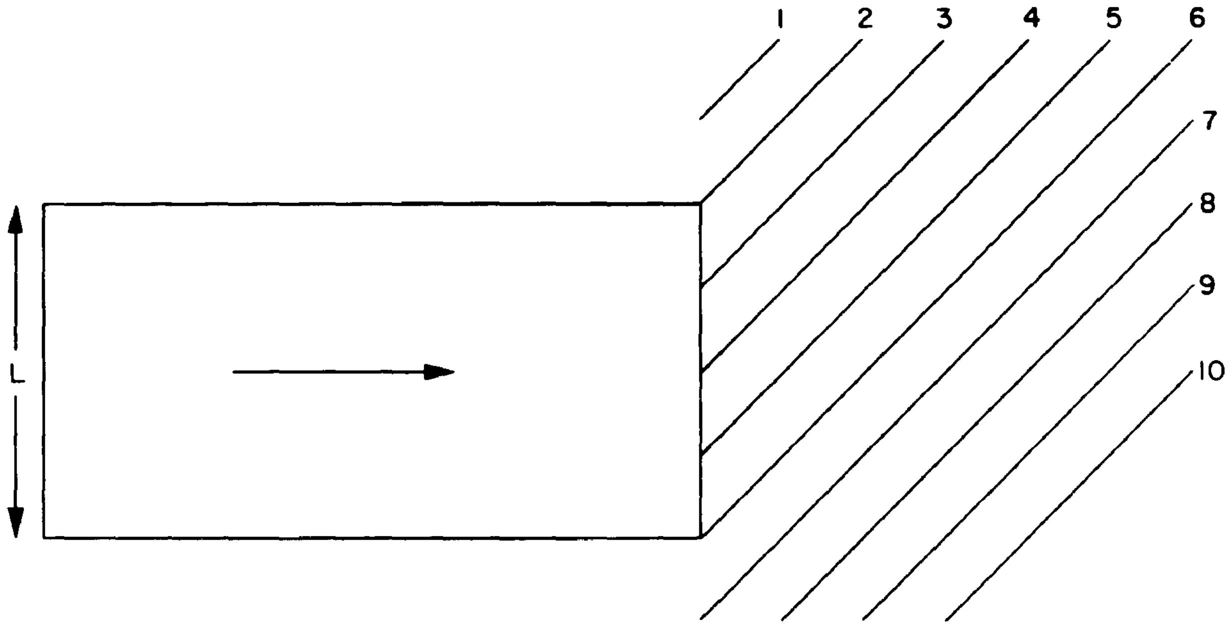


a. Trajectories Considered

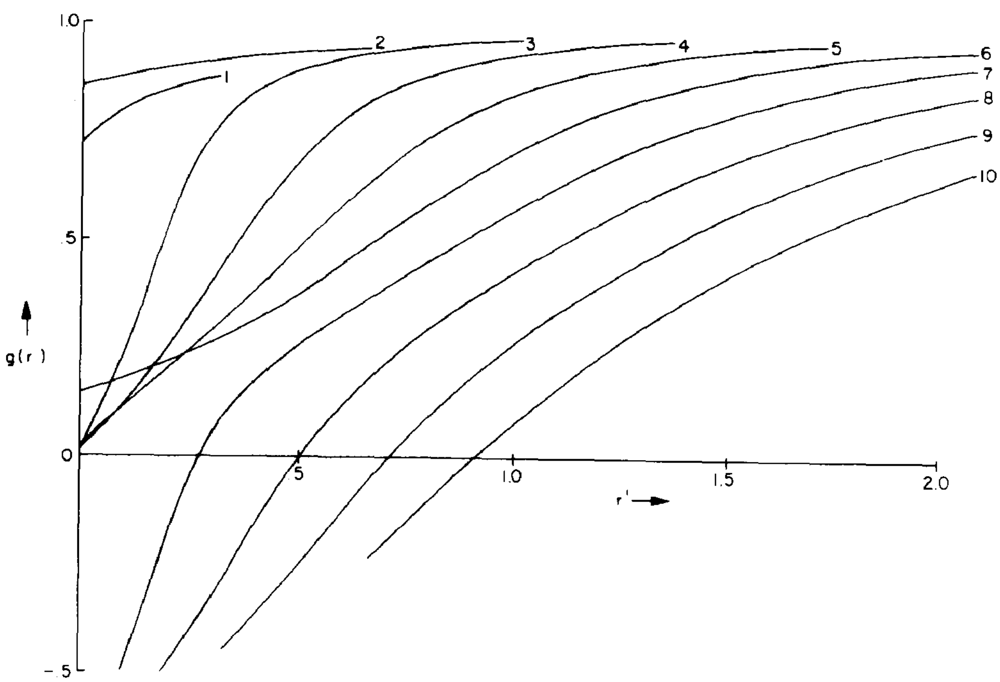


b. Variation of Doppler Frequency

Figure 3-6 Variation of Doppler Frequency with Trajectory (Different Trajectories)

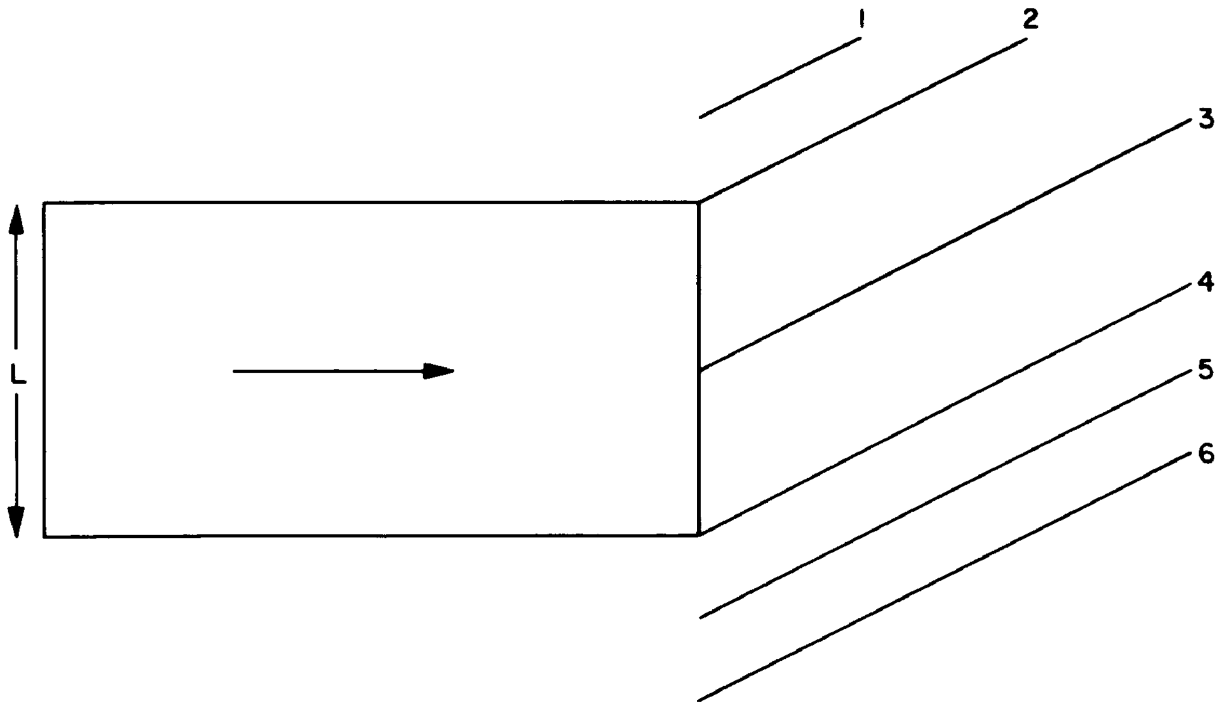


a. Trajectories Considered

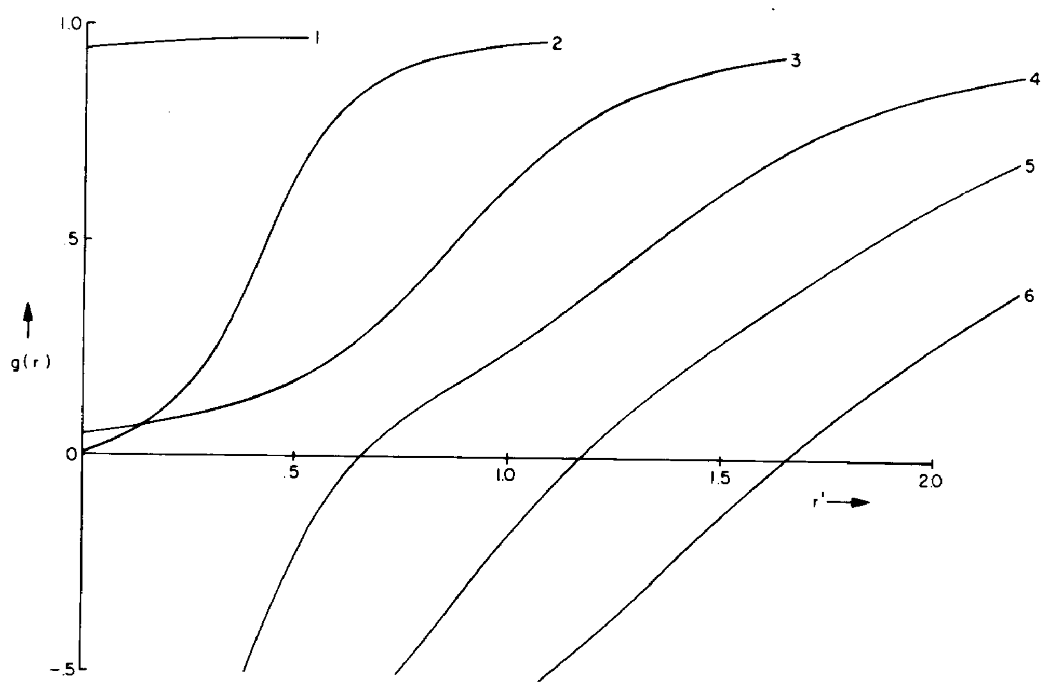


b. Variation of Doppler Frequency

Figure 3-7 Variation of Doppler Frequency with Trajectory (Different Trajectories)

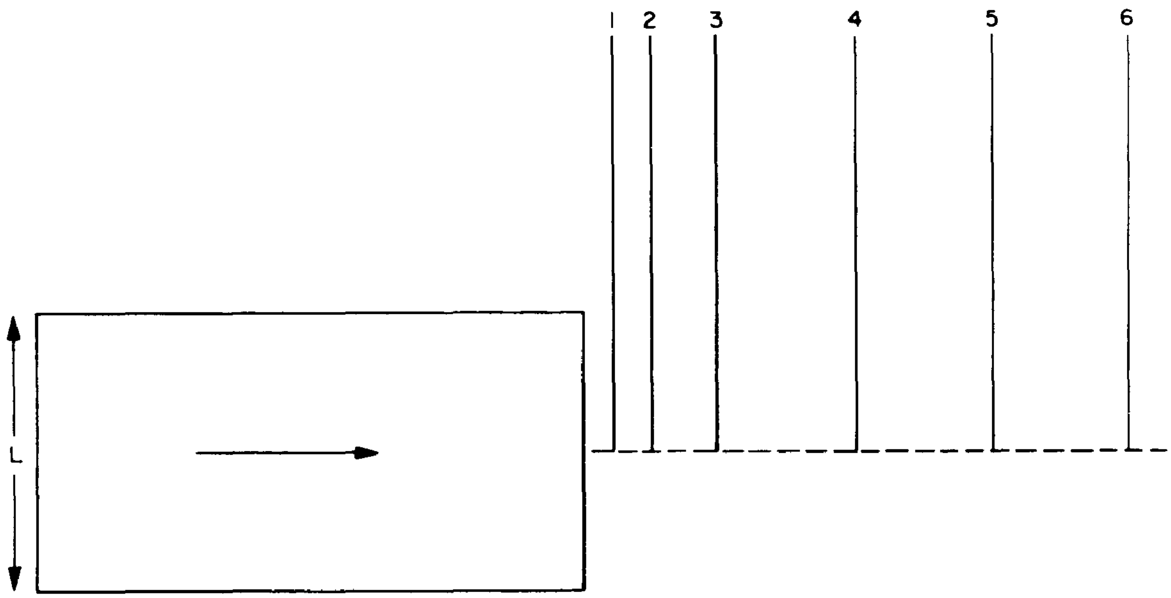


a. Trajectories Considered

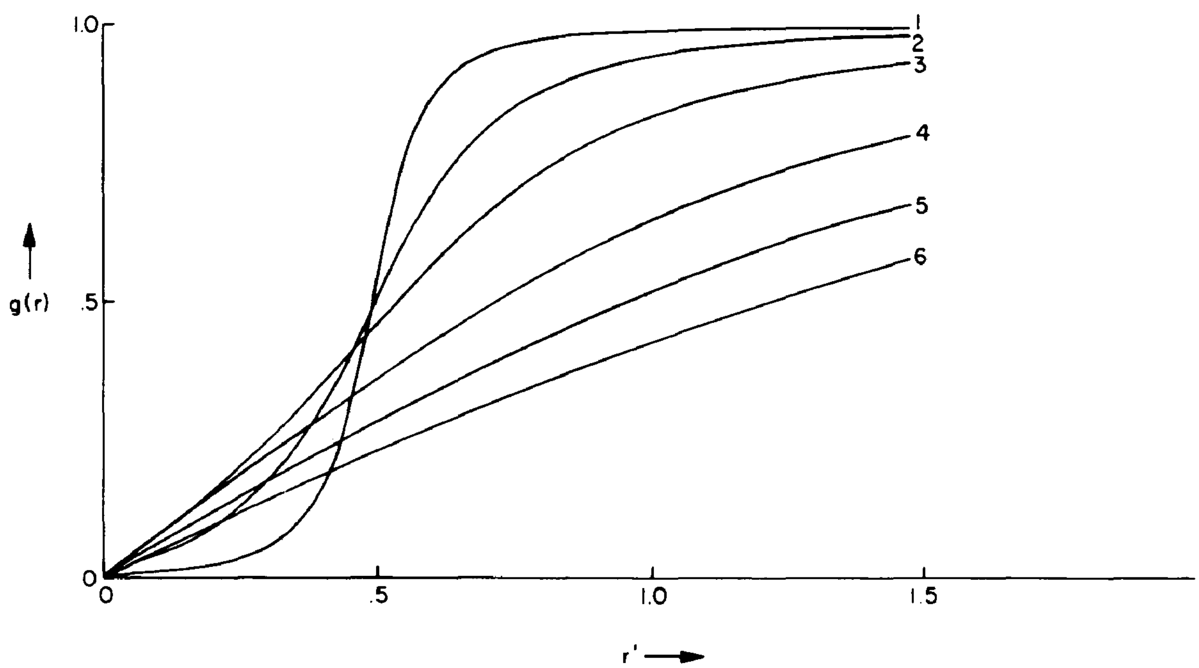


b. Variation of Doppler Frequency

Figure 3-8 Variation of Doppler Frequency with Trajectory (Different Trajectories)



a. Trajectories Considered



b. Variation of Doppler Frequency

Figure 3-9 Variation of Doppler Frequency with Trajectory (Different Trajectories)

doppler frequency along those paths (b).

3.1.2.3 Region of Coverage - As stated above, position discrimination is almost entirely dependent upon antenna patterns and their interrelationship. In order to determine a reasonable estimate of the optimal patterns, computer calculations have been made for a variety of antenna beamwidths and aiming point. While the desirability of various patterns is to some extent dependent on the desired characteristics of the system as a whole, sharp cutoff (decrease in sensitivity) is necessary in front and (particularly) on the side, to avoid any near-miss activations. At the same time, it is important to have fairly uniform coverage across the front of the vehicle.

The calculations which are described in greater detail in Appendix A, assume an isotropic scattering target and $1/R^2$ loss on both transmitting and receiving paths, with antenna gain A taken as $A = 30 [\cos(51.68\ \theta/w) - 1]$, with θ the angle (in degrees) off axis, and w the 3-dB beamwidth of the antenna. This approximation is quite accurate up to $\theta = 3.5\ w$. The quantity determined is received signal power, normalized to a maximum value of zero dB. Plots of system sensitivity contours (top view) are shown in Figures 3-10 to 3-12; these represent results obtained in considering a large variety of cases. The horizontal and vertical scale factors are the same. "ANT AIM" is measured in degrees from a normal to the R-T line, and in meters from the R-T line. The contours plotted are for 0 dB (maximum sensitivity)

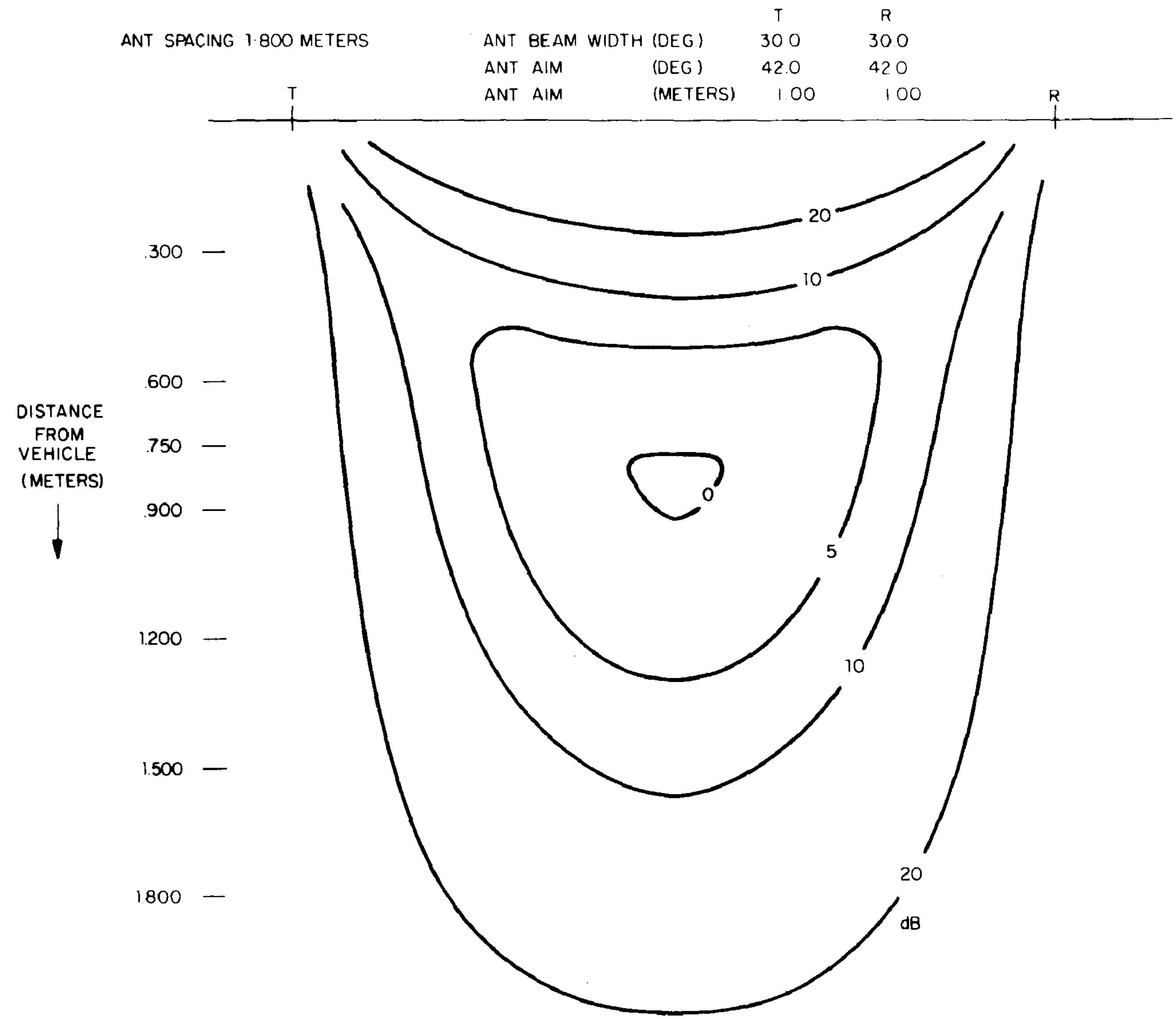


Figure 3-10 Calculated Detection Sensitivity Pattern

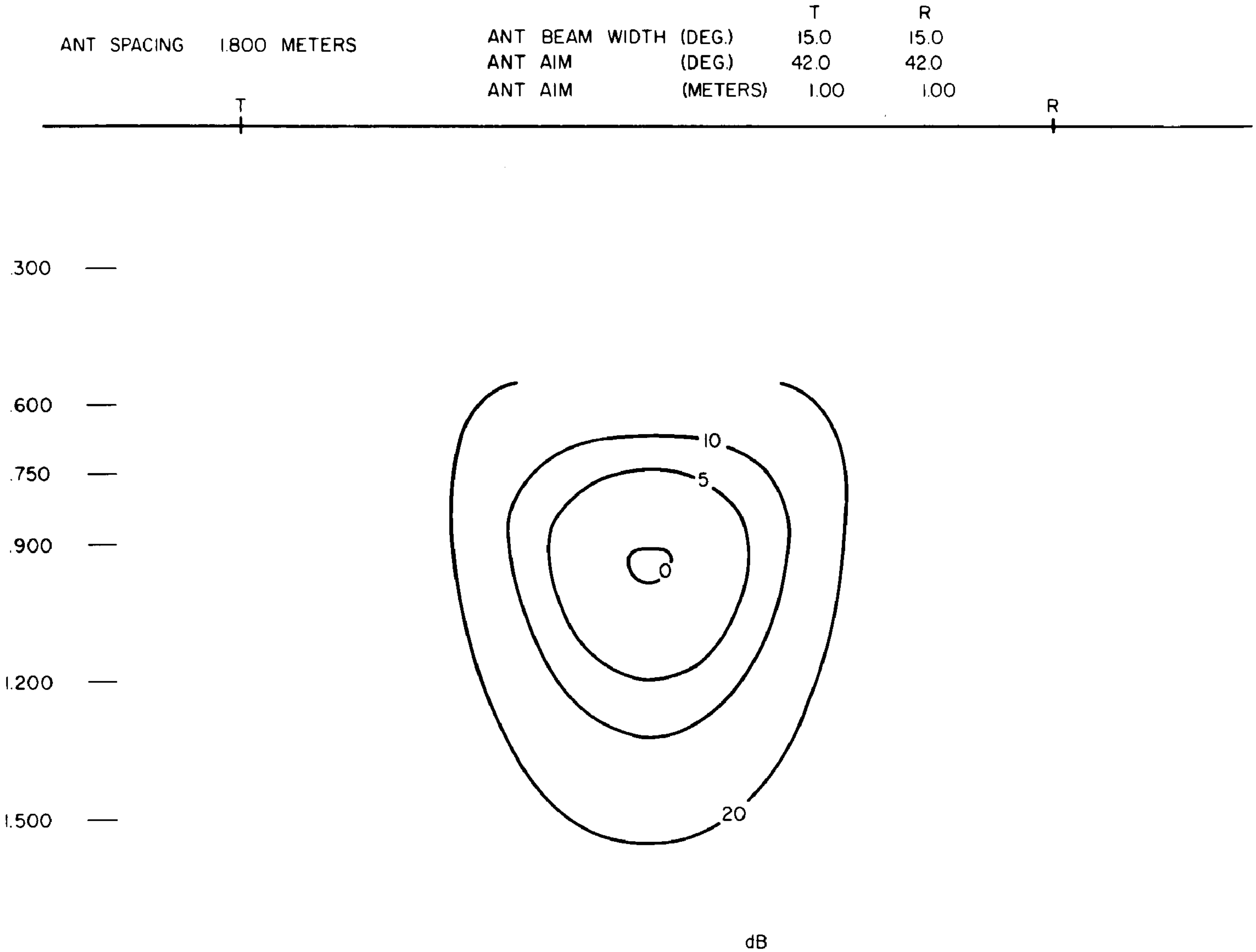


Figure 3-11 Calculated Detection Sensitivity Pattern

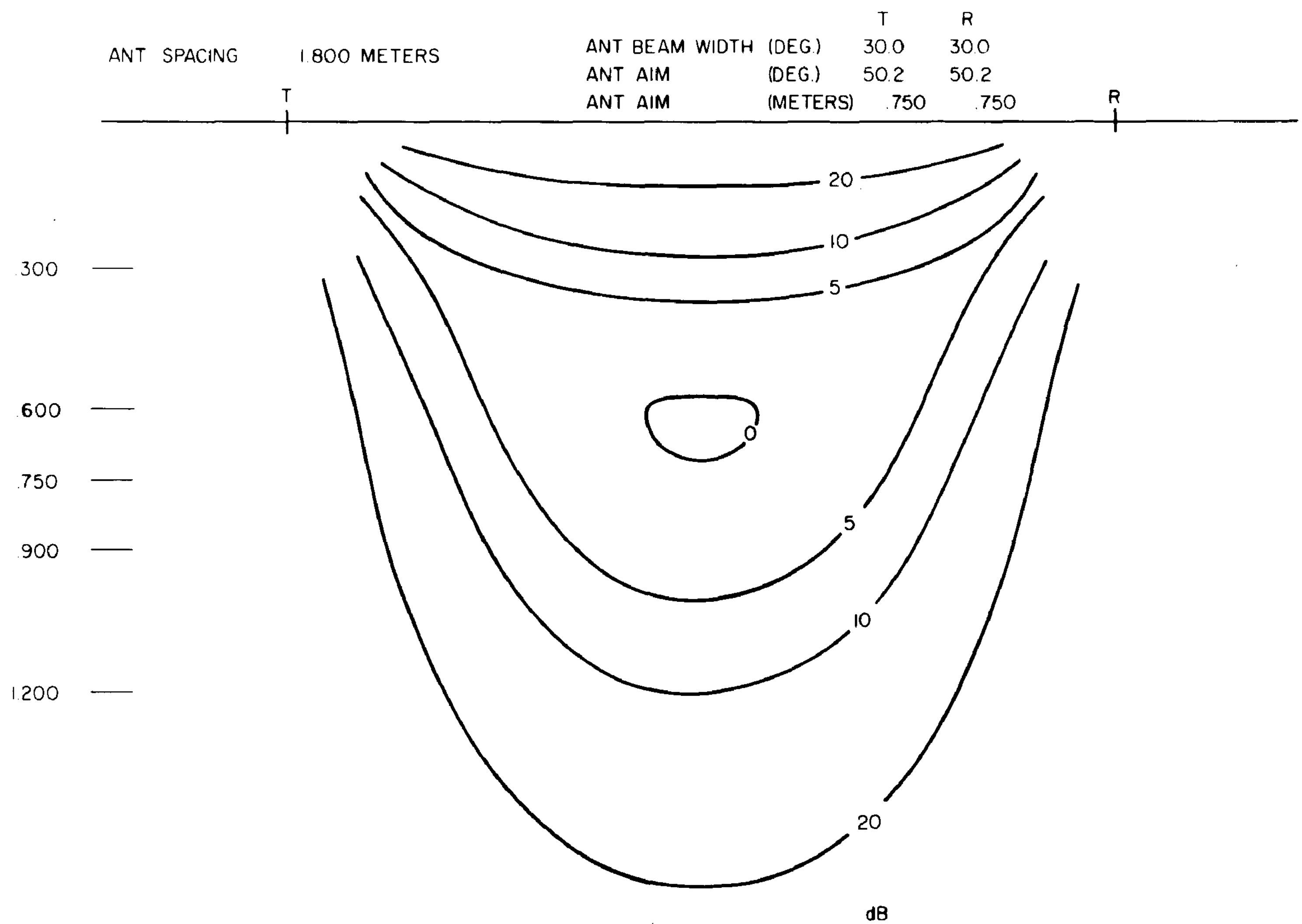


Figure 3-12 Calculated Detection Sensitivity Pattern

and returns weaker by 5, 10 and 20 dB. For the crash sensing application the 5 dB contour approximately defines the region of system response. It is worth noting that the most simple approximation, as used previously for Figure 3-1 gives a fairly good measure of the sensitivity contour, except that the pattern is shifted to somewhat greater ranges. This is illustrated in Figure 3-13 which repeats Figure 3-10 (0 and 5 dB only) with superimposed lines delineating idealized antenna patterns. (As indicated, the calculations assume the target to be an ideal scatterer; the alternative assumption of perfect reflection is not found to change the contours significantly. The acutal situation is between these two extremes, and is discussed at some length in Chapter IV.)

3.1.2.4 A Dual System - The regions of maximum sensitivity shown in Figures 3-10 to 3-12 fall short of ideal coverage. Angled impacts and frontal corner collisions may be missed. These weaknesses can be mitigated by use of a dual system, as indicated in Figure 3-14. The basic system is non-symmetric in both beamwidth and aims, as shown in Figure 3-14a and a second set of antennas, symmetric to the first pair, is added (Figure 3-14b) providing a net sensitivity region as shown in Figure 3-14c. The same process is illustrated in terms of computer calculations in Figures 3-15 and 3-16; another case is shown in Figure 3-17. Figure 3-18 is analogous to 3-13, and shows the relationship of the most simple approximation to careful computations in the dual case. This approach permits coverage far closer to the ideal.

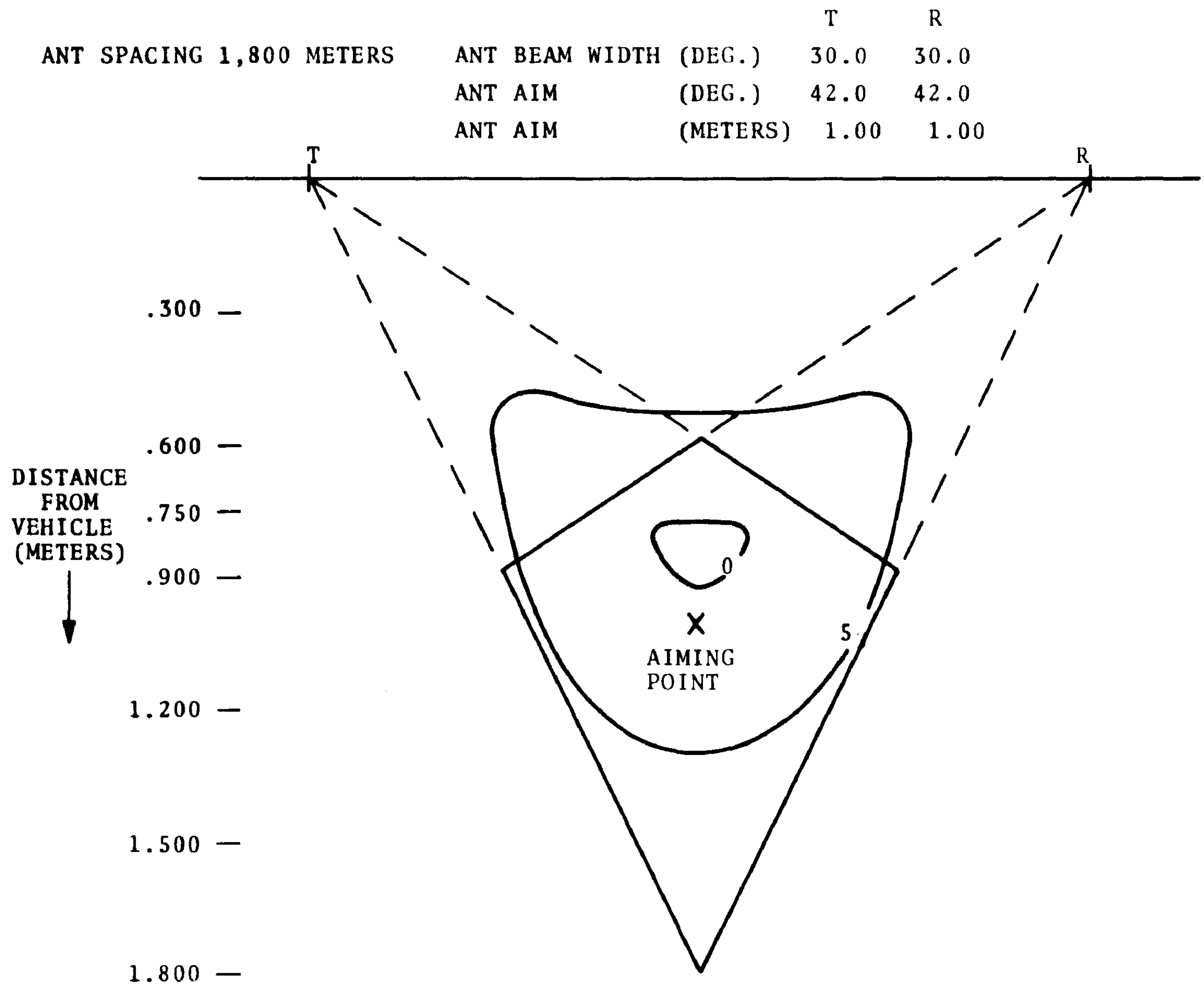


Figure 3-13 Comparison of Sensitivity Patterns: Simple Approximation vs. Detailed Calculation

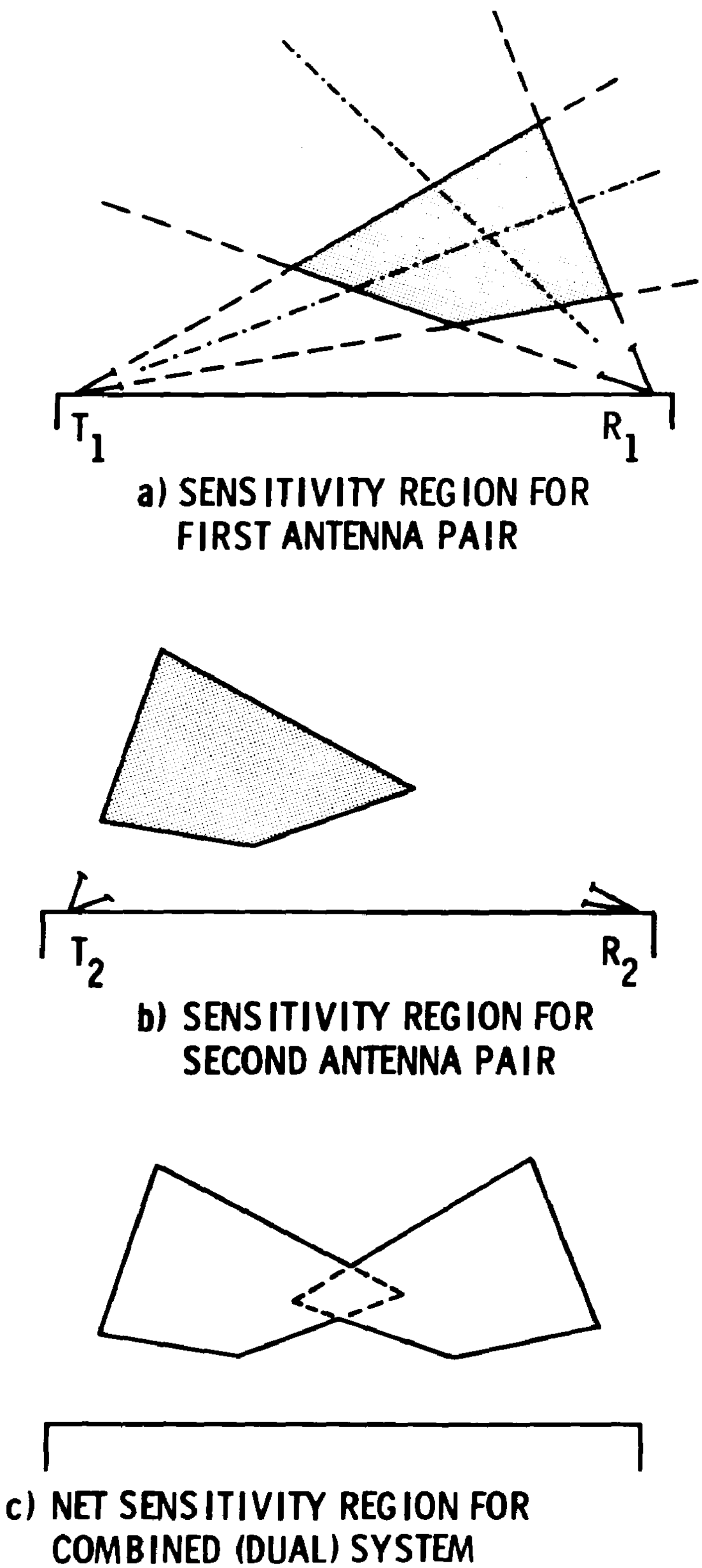


Figure 3-14 Derivation of Dual Antenna System

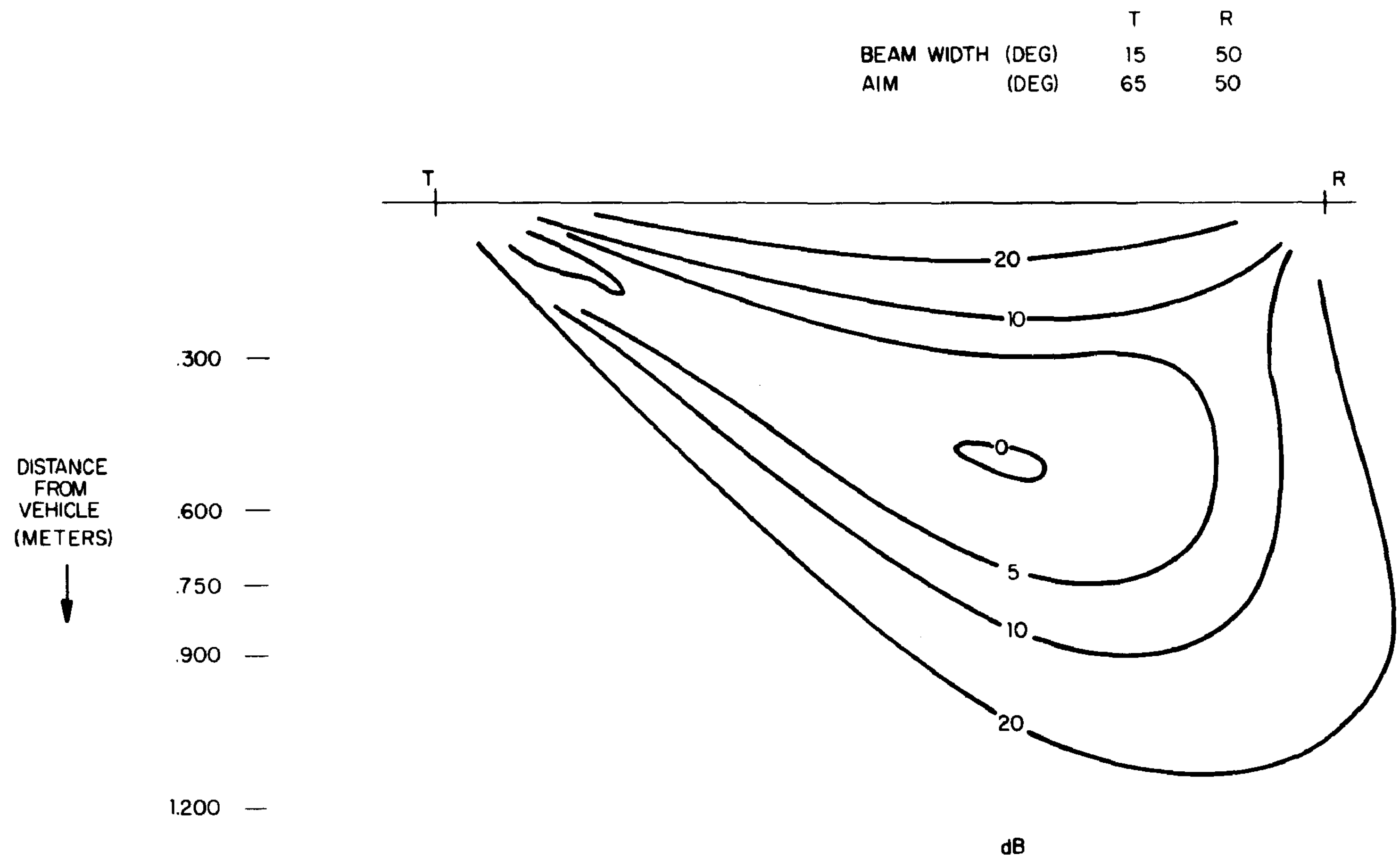


Figure 3-15 Detection Sensitivity Pattern for Half of Dual System

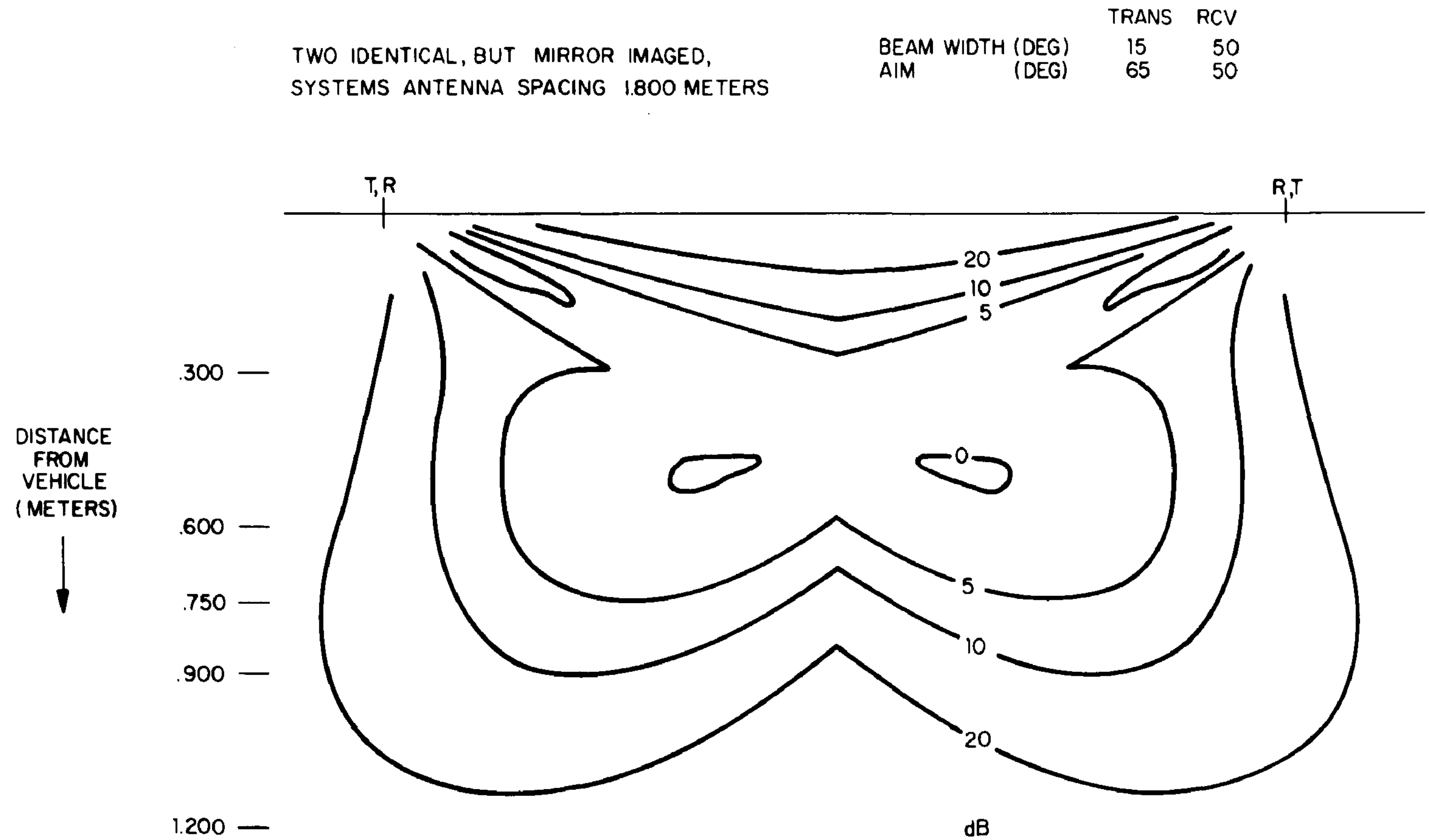


Figure 3-16 Detection Sensitivity Pattern Formed from Superposition of Two Systems as in Figure 3-15

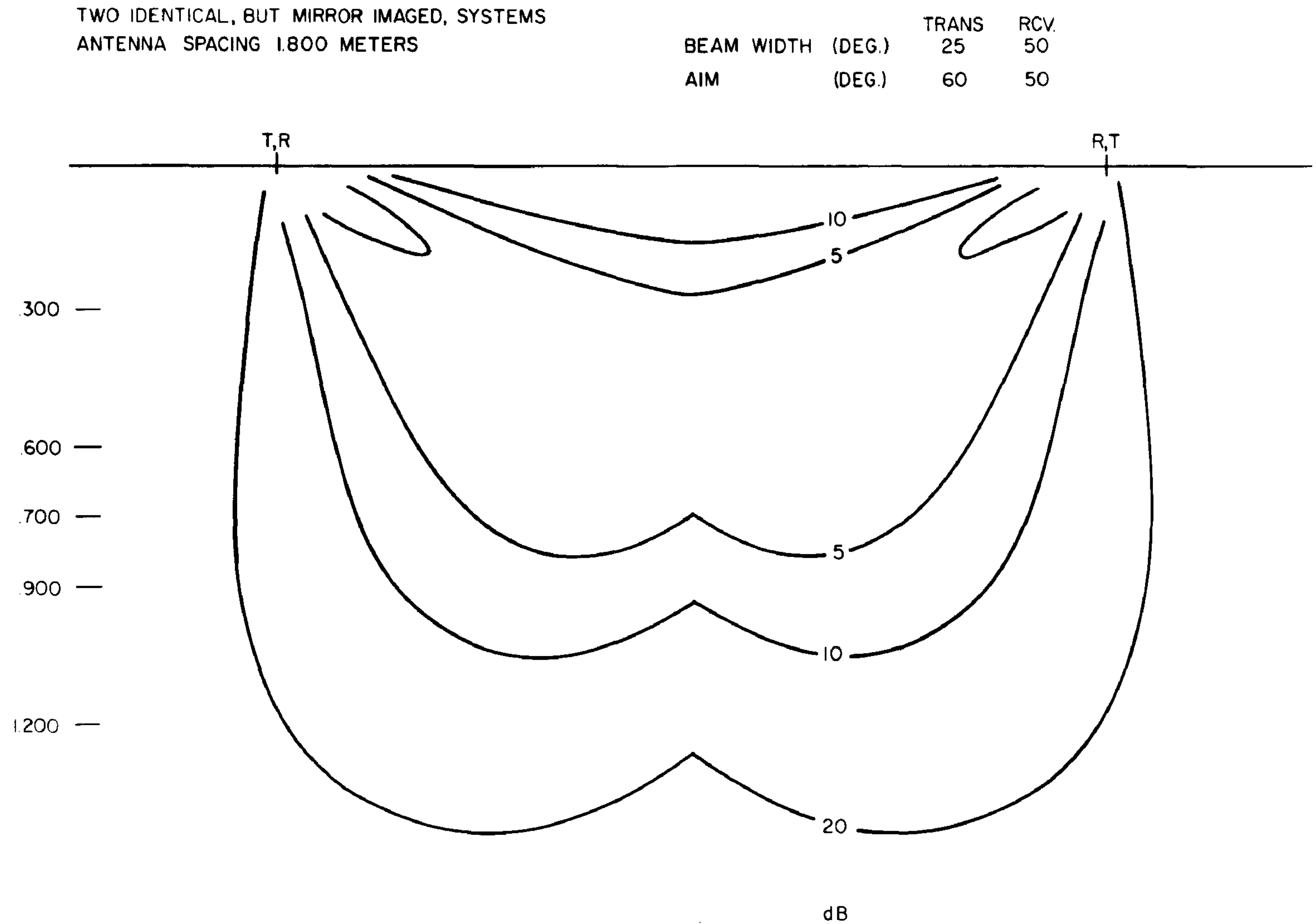


Figure 3-17 Detection Sensitivity Pattern for Dual System (Second Case)

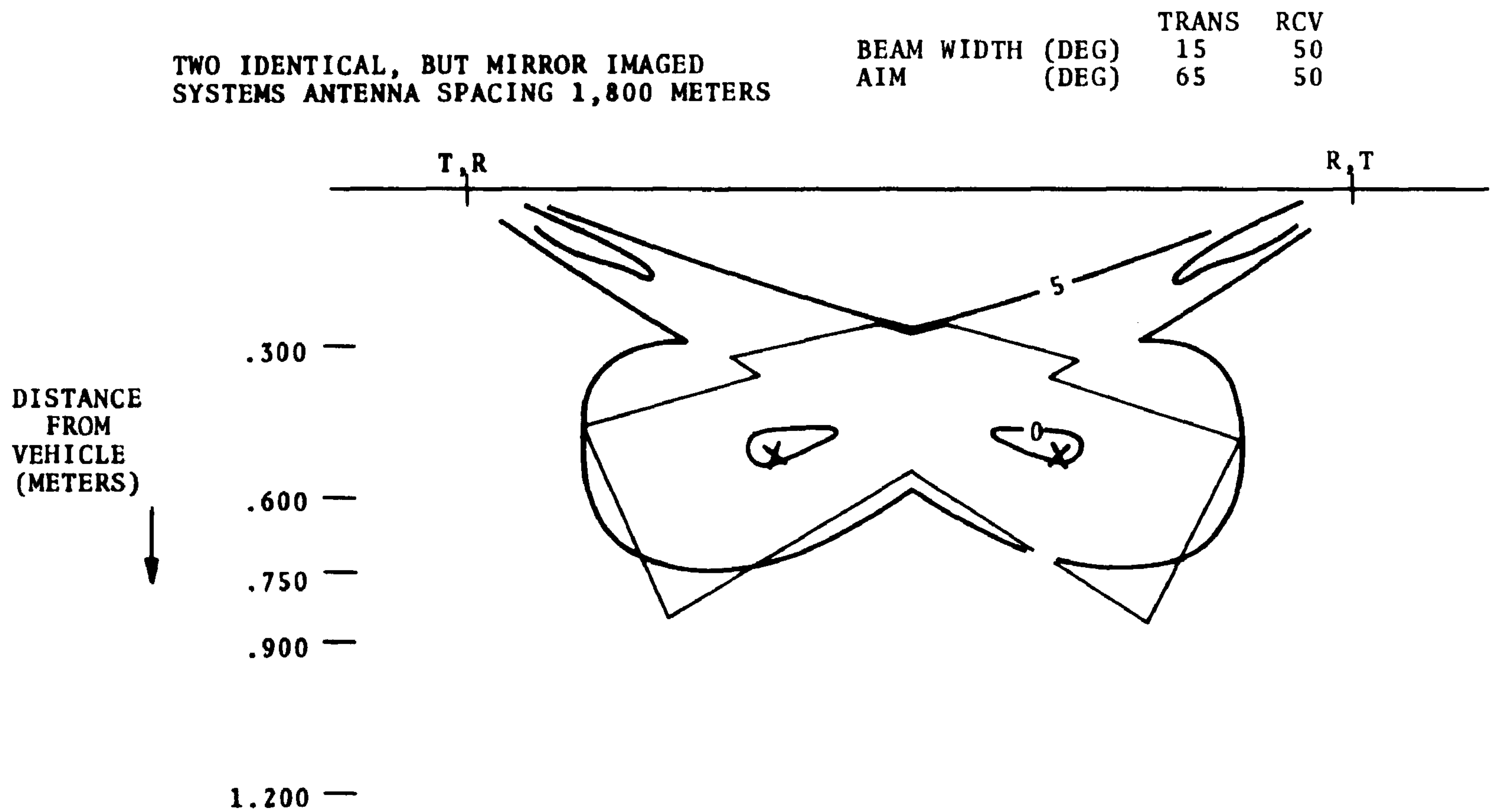


Figure 3-18 Comparison of Sensitivity Patterns for Dual System: Simple Approximation vs. Detailed Calculation

Here, to an even greater extent than above, there is a very large number of possible configurations; only a selection representative of the more desirable shapes is shown. It is found - not surprisingly - that this type of pattern can be obtained only for protection near to the vehicle - a distance of approximately .3 to .5 vehicle-widths. However, this is quite suitable to the crash sensor application in question.

3.1.3 Signal Processing

3.1.3.1 Introduction - As indicated previously, the use of a bistatic configuration permits consideration of a basically very simple transmitter/receiver/signal processor. CW operation, utilizing solid state oscillatory diodes, requires only a regulated 12V. DC power supply; there is no modulator involved. Similarly, the receiver essentially consists of a mixer diode, with local oscillator power provided by sampling the transmitted signal. The only additional element required is an audio frequency amplifier with a pass band of approximately 300-500 Hz and 20 - 30 dB gain to bring the doppler signal up to a convenient level for processing.

The overall system must make three basic discriminations; position, velocity, and target size. "Size" is used here in a general sense. In the ideal case, this would mean target hazard or lethality. Since these are very complex quantities, it is difficult to imagine any anticipatory or predictive sensor which can respond exactly as desired. However, it is possible that sufficient information can be obtained by means of radar to permit a deployment decision which will be correct sufficiently often to provide a system of good overall effectiveness.

As described above, position discrimination sufficient to the task is inherent in the antenna configuration. Relative velocity is directly measurable from the frequency of the doppler signal. Further, as with position information, it is not really necessary to know the exact velocity; the only determination required is whether the closing rate is above or below a specified threshold. The measurement of "size," as operationally defined in this system, is twofold: target microwave reflectivity (as measured by the amplitude of the doppler signal, proportional to recieved signal amplitude) must be above a given threshold, and this threshold must be exceeded for a specified number of doppler cycles. The basic system is seen in Figure 3-19. This latter requirement serves two functions: in addition to assuring that a target is sufficiently large to be at least partially in the region of maximum sensitivity over a significant distance, this greatly reduces possible malfunction due to circuit transients and interfering signals (see Chapter 7). Since each doppler cycle corresponds to a target movement of one-half wavelength, an 8-cycle requirement (for example) means that the target must move through a distance of four wavelengths (12 cm. at 10 gHz) to trigger the system.

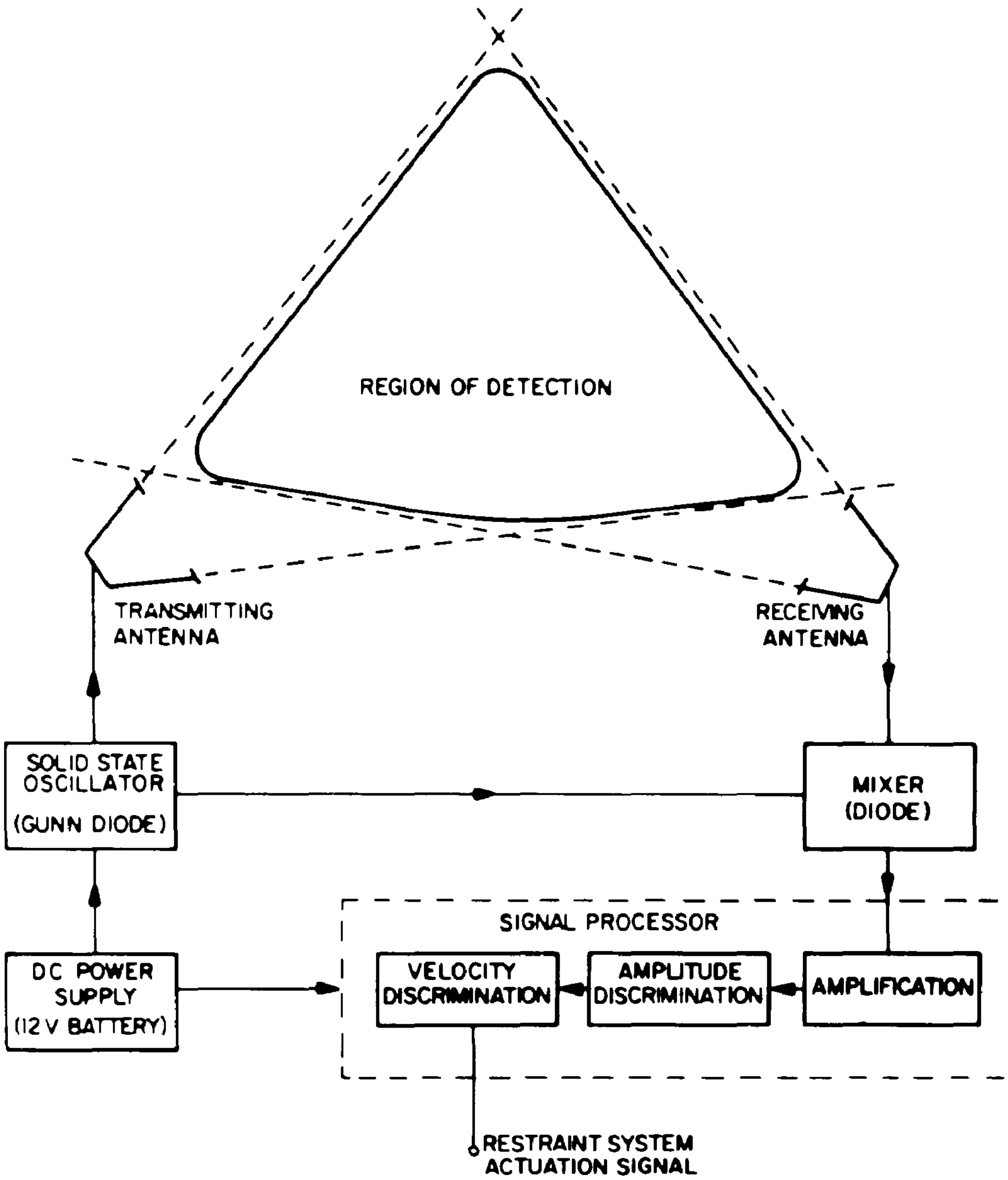


Figure 3-19 Basic Bistatic CW Doppler Radar Sensor Configuration

3.1.3.2 Basic Circuit - Linear Realization - This circuit was described in detail in Report DOT-NHTSA-TSC-71-3 and a brief description will be given here only for completeness. The circuit is shown in block diagram in Figure 3-20. The amplified doppler input is passed through a high pass filter for velocity discrimination. (Significant filtering is also carried out in the amplifier). It is then applied to a differential comparator (sense amplifier). The essential characteristics of such devices are indicated in Figure 3-21. The proper bias, V_T, converts any applied sinusoidal input signal, V_i, into a constant -.5 V if below threshold ($V_i < V_T$), or into a rectangular wave of 3.5 V p-p amplitude for any above threshold value of V_i ($V_i > V_T$). Other than the range just above threshold, the duty cycle of the output is only mildly dependent on the amplitude of V_i, thus being of little significance in a linear circuit, and none in a digital circuit. Use of this circuit establishes a sharp triggering threshold for signal magnitude, adjustable via V_T during system development. The output of this stage is applied to a simple diode-RC second detector which reaches a final triggering threshold only after integrating 4 to 5 processed doppler cycles (above the velocity and magnitude thresholds). The actuation criteria for this circuit is illustrated in Figure 3-22.

3.1.3.3 Basic Circuit - Digital Realization - Experience with the linear circuit led to development of the circuit of Figure 3-23 which makes use of digital techniques. No filtering is used per se, but rather the output of the comparator triggers a monostable multivibrator and is also applied to an 8:1 counter/divider.

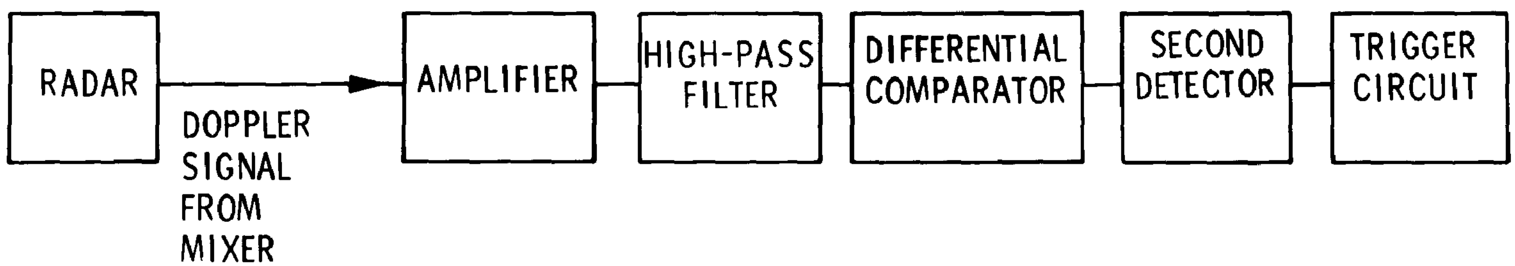


Figure 3-20 Block Diagram of Basic Linear Signal Processing Circuit

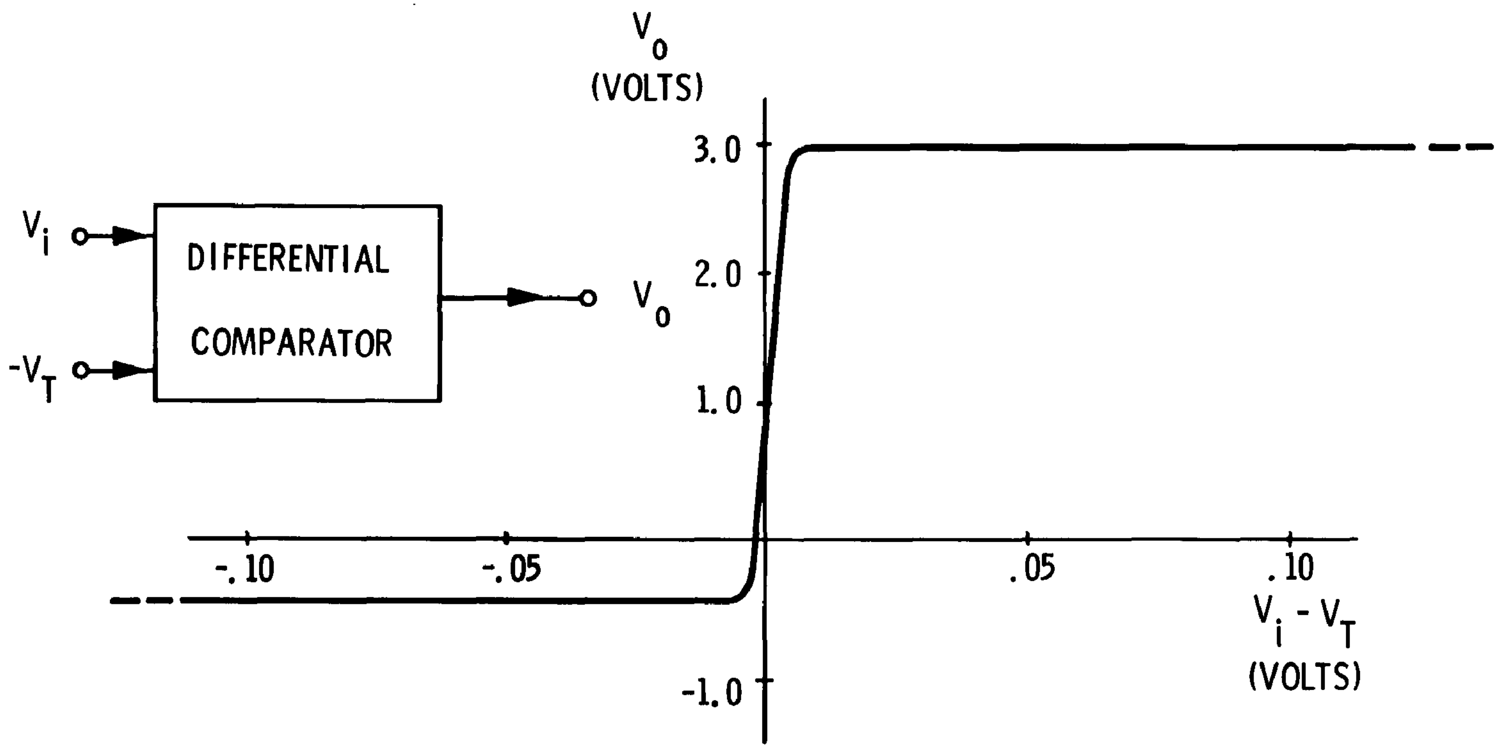


Figure 3-21 Characteristics of Differential Comparator

SIMPLE LINEAR CRASH SENSOR OPERATION

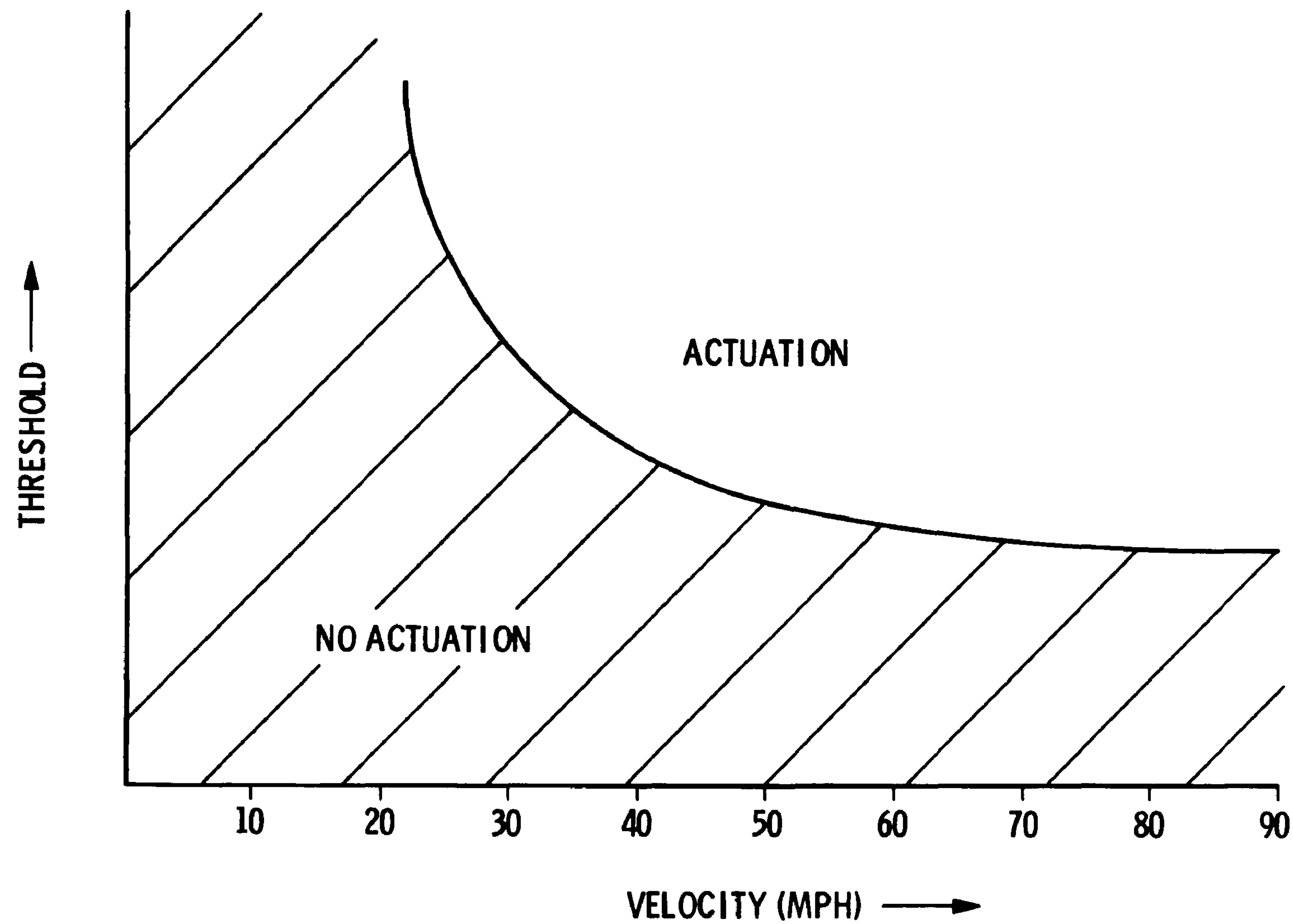


Figure 3-22 Actuation Criteria for Basic Linear Sensor

The multivibrator normally provides a reset signal to the counter, holding it at zero. However, when triggered, the reset input is removed for 28 msec (in this example), until the multivibrator returns to its stable state and the counter output is returned to a zero count. Thus, the divider will only have an 8-bit output count if eight above-threshold doppler cycles are received in the 28 msec. period following arrival of first pulse to the multivibrator. A total of nine counts in 28 msec corresponds to an extremely sharp cutoff frequency of 321 Hz. (These illustrative numbers are typical of a practical case.) If one includes consideration of the effect of position on received doppler frequency, as discussed above and shown previously in Figures 3-4 to 3-9, this corresponds to a "true" doppler frequency of approximately 450 Hz at a distance of L/2 in front of the vehicle, or a 15 MPH velocity threshold. This circuit also incorporates the cycle counting function carried out separately (in the second detector) for the linear circuit. A nine-cycle required count implies target movement through approximately 14 cm for restraint activation to occur, a reasonable value. However, it would be easy to use a different criteria should system considerations require. The basic frequency amplitude triggering are illustrated in Figure 3-23 and 3-24.

3.1.3.4 Basic Hybrid Concept - The radar signature results (Chapter 4) suggests that a restraint system dependent solely upon a radar sensor for actuation will not have satisfactory characteristics, due primarily to excessive probability of

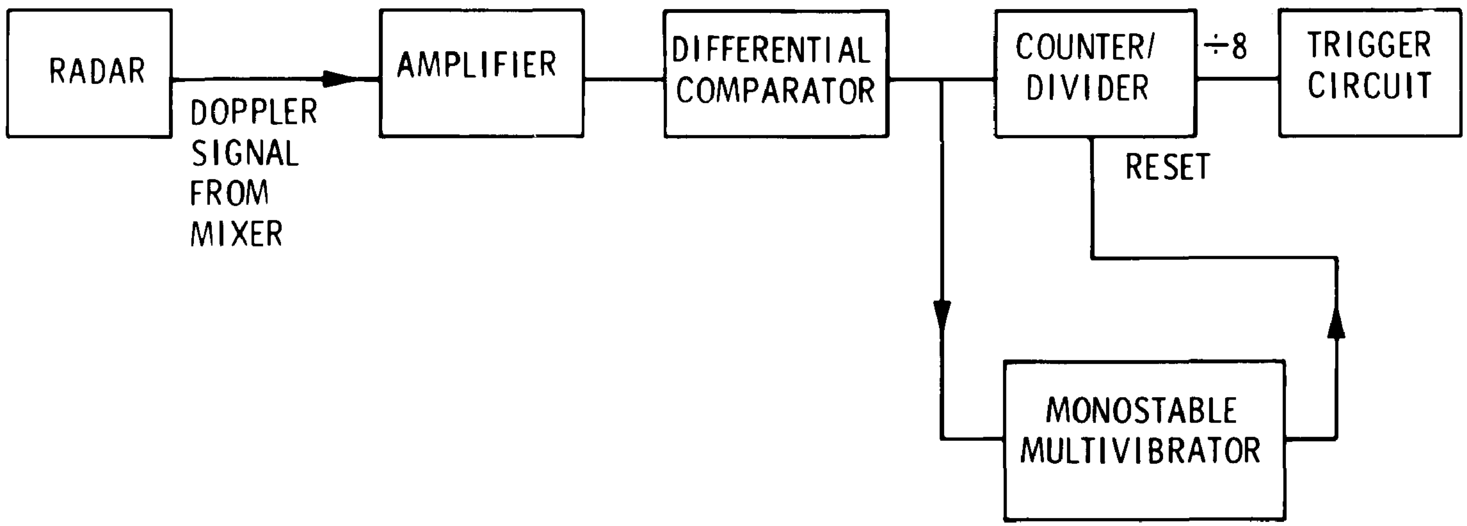


Figure 3-23 Block Diagram of Basic Digital Signal Processing Circuit

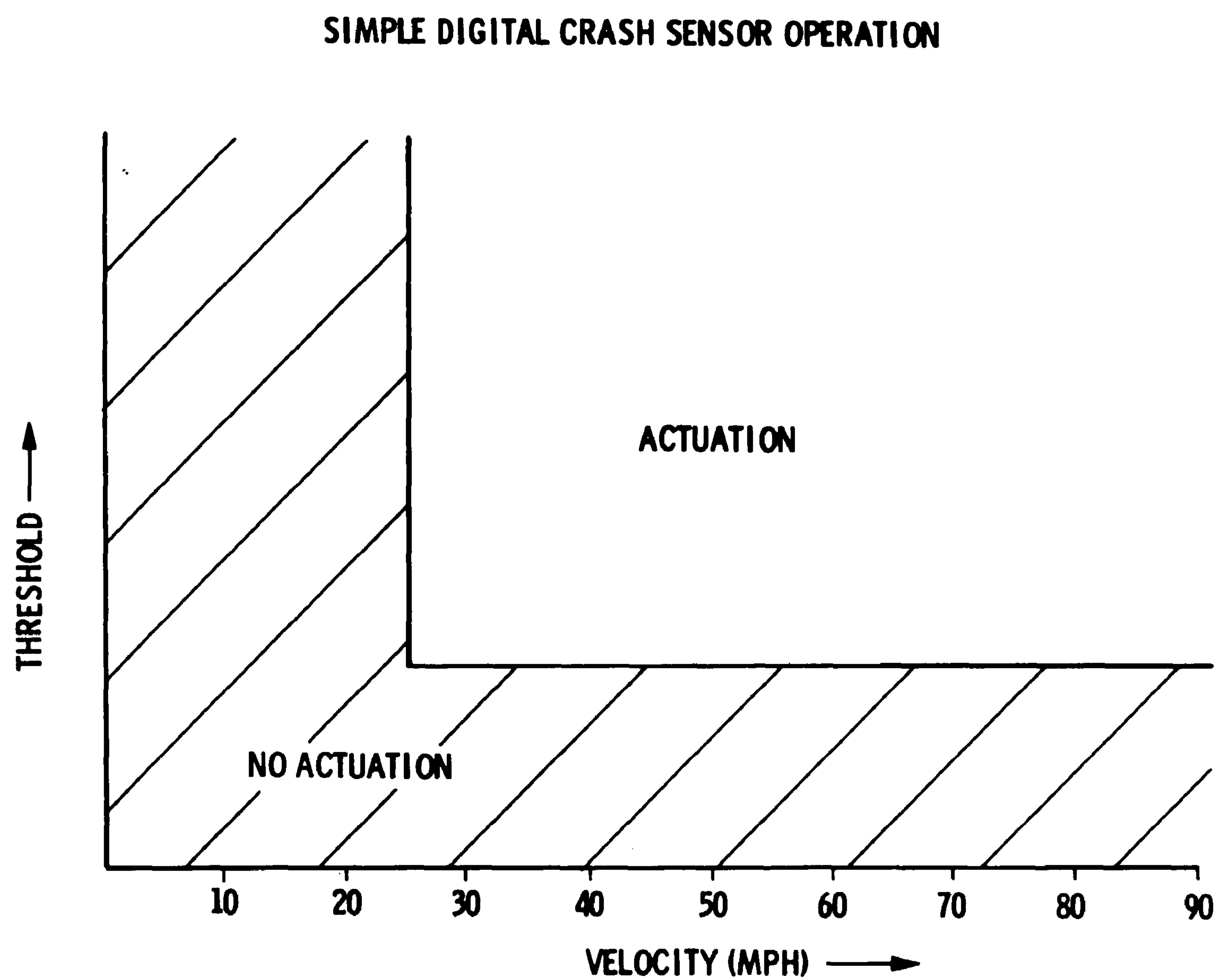


Figure 3-24 Actuation Criteria for Basic Digital Sensor

inadvertent actuation if the threshold is low enough to provide triggering for a high percentage of "real" targets. However, it is useful to consider the situation separately for different ranges of impact velocity. Up to moderate speed--perhaps 30 MPH--it currently appears that electro-mechanical (decelerometer) sensors of the type now used in prototype systems are satisfactory. On the other hand, at high velocities--above (for example) 45 MPH--the penalty for non-actuation is great, and the most beneficial results are obtained if such actuation is prior to impact. Recall from Chapter 1 restraint systems do offer substantial protection even at very high impact speeds if the basic vehicle structure permits and triggering occurs sufficiently early. At the same time, the cost of inadvertent actuation is probably only marginally greater than for low velocities. It may be assumed that few accidents at such speeds will be minor, so that almost any impact with a target of substantial size will be serious. Also, many of the potential "false alarm" targets are more likely to be encountered at low speeds--street signs, etc. In summary, the advantages of anticipatory sensing increase sharply with impact velocity, while the disadvantages may be expected to remain relatively unchanged.

Thus, the optimal sensor compromise, cost permitting, may well involve use of an anticipatory (radar) sensor at higher speeds, with mechanical sensing at low impact velocities. In the intermediate range (30 to 45 MPH in this example) one might properly be hesitant to put total faith in radar, but full restraint effectiveness allows only a very short time budget--sensing must be completed within a few milliseconds after impact. While this is too small a time for decelerometers, it is (at least for the larger cars) sufficient to permit use of a relatively fast (1 to 5 msec) low-threshold impact sensor, possibly incorporated into the front (energy-absorbing) bumper for crash confirmation. (Such an impact sensor could not be used independently, as it does not permit sufficient discrimination between relatively minor, low-speed accidents and higher speed collisions with more massive objects.) This somewhat ambiguous impact indication, immediately following radar sensing of a relatively high closing rate with a target of substantial size, provides an overall system in which considerable confidence can be placed. In essence, the requirement for both radar triggering and mechanical confirmation should eliminate most inadvertent actuations but will still provide sufficiently timely restraint deployment in the intermediate speed range. Figure 3-25 is a block diagram of a circuit to realize such operation. The actuation criteria for such a system is indicated in Figure 3-26.

3.1.3.5 Elaborations on the Hybrid Concept - One can readily imagine a more complex set of criteria without substantial change in the required circuitry. It is argued above that, in essence, the radar indication is to be utilized not at all at low speeds, in conjunction with an impact sensor at moderate speeds, and alone only for the higher velocities. This step variation, as indicated in Figure 3-26 can be replaced by a continuous one, in which the radar actuation threshold is made a function of velocity. This can easily be accomplished by means of high pass filters in the

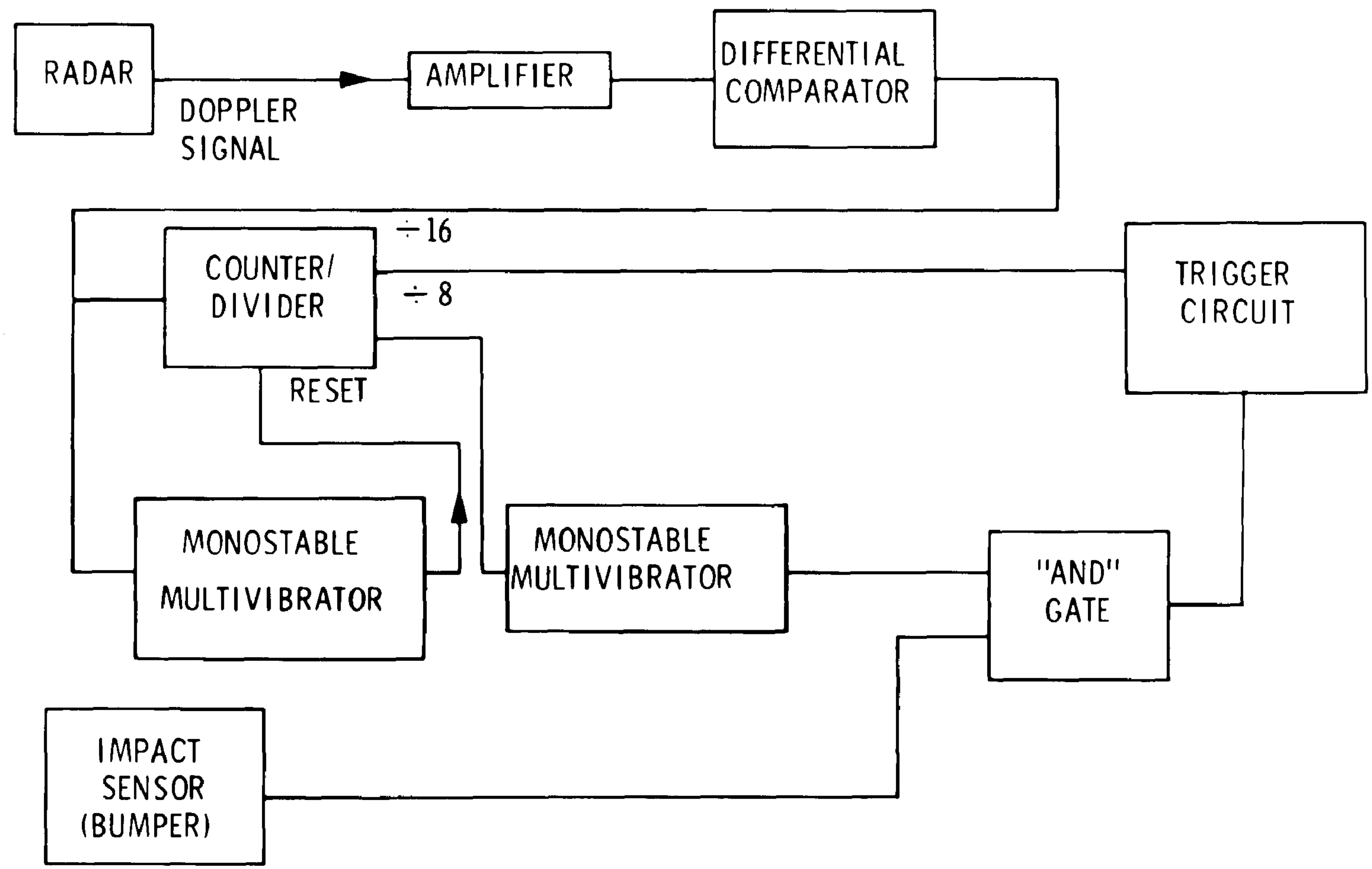


Figure 3-25 Block Diagram of Digital Hybrid Signal Processing Circuit

HYBRID, DIGITAL CRASH SENSOR OPERATION

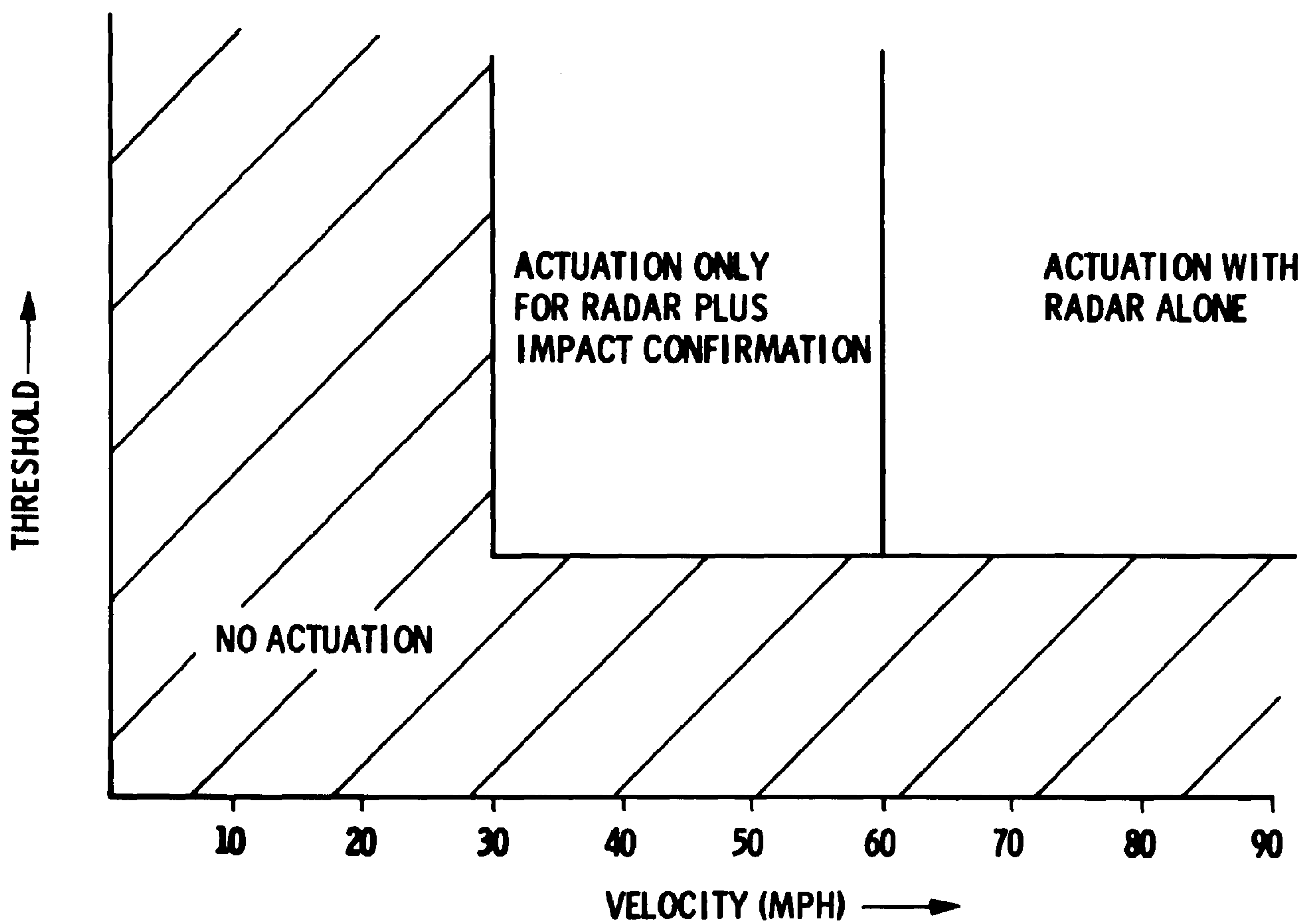


Figure 3-26 Actuation Criteria for Digital Hybrid Sensor

signal processing circuit. A simple example is shown in the block diagram of Figure 3-27, with the resulting characteristic (for the hybrid case) shown in Figure 3-28 and in Figure 3-29 for a two level system. The optimal form of these curves is, of course, a function of vehicle and restraint system crash characteristics, the spectrum of collision objects, and radar performance.

3.1.4 Experimental Systems

Early in this research program a prototype sensor utilizing the basic linear circuit (Figures 3-20 and 3-21) was constructed and tested both in the laboratory (Figure 3-30) and in a test vehicle (Figure 3-31). This permitted early determination of a variety of operating characteristics. Figure 3-32, for example, shows calculated sensitivity curves (a) and measured contours (b). Observation of the amplified, unfiltered doppler return from a variety of targets was observed in roll-up tests (Figure 3-33). A general discussion of microwave characteristics of various targets will be found in Chapter 4. These test procedures have been utilized with digital and hybrid systems as well, and the test vehicle has been driven several thousand miles. No basic problems or incompatibilities have been found.

3.2 SONAR

The ultrasonic acoustic (sonar) crash sensor considered at TSC is based on exactly the same principles of operation as the microwave sensor: it is a bistatic cw doppler system, with

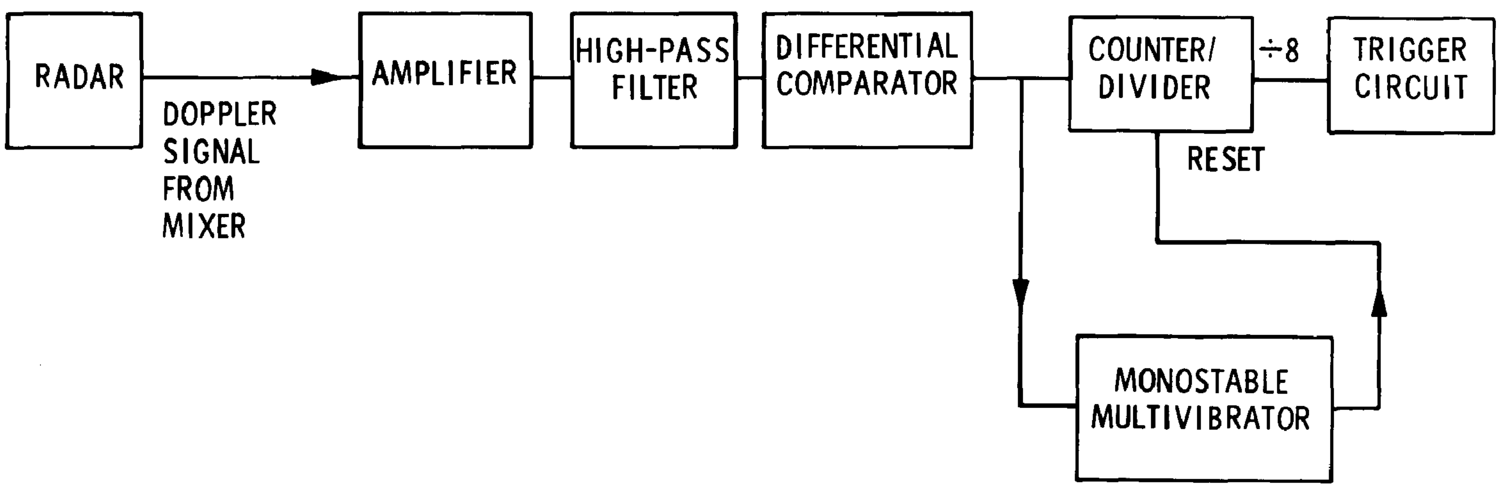


Figure 3-27 Block Diagram of Variable Threshold Digital Sensor

HYBRID, DIGITAL/LINEAR SINGLE THRESHOLD CRASH SENSOR OPERATION

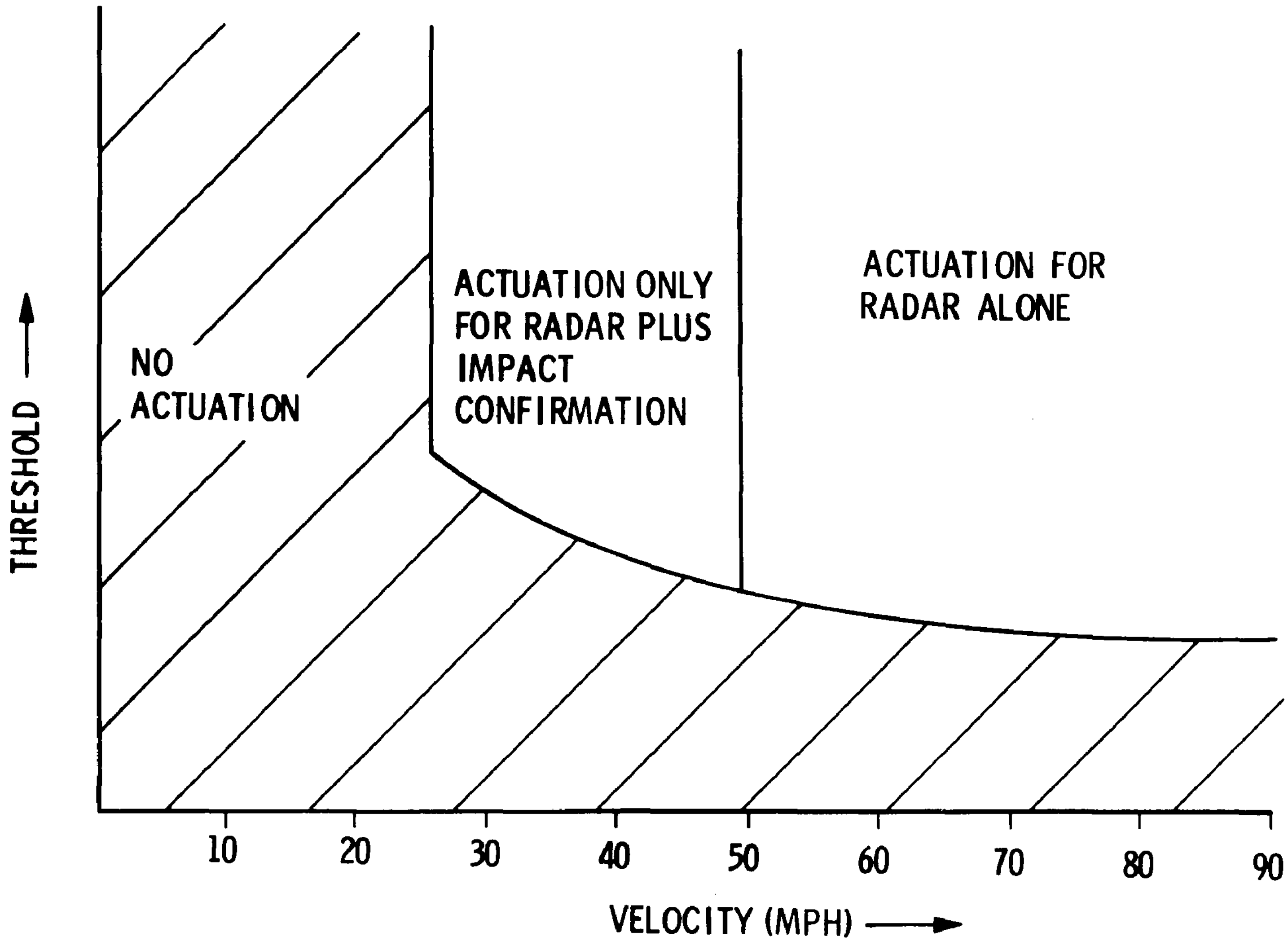


Figure 3-28 Actuation Criteria for Single Threshold Hybrid Sensor

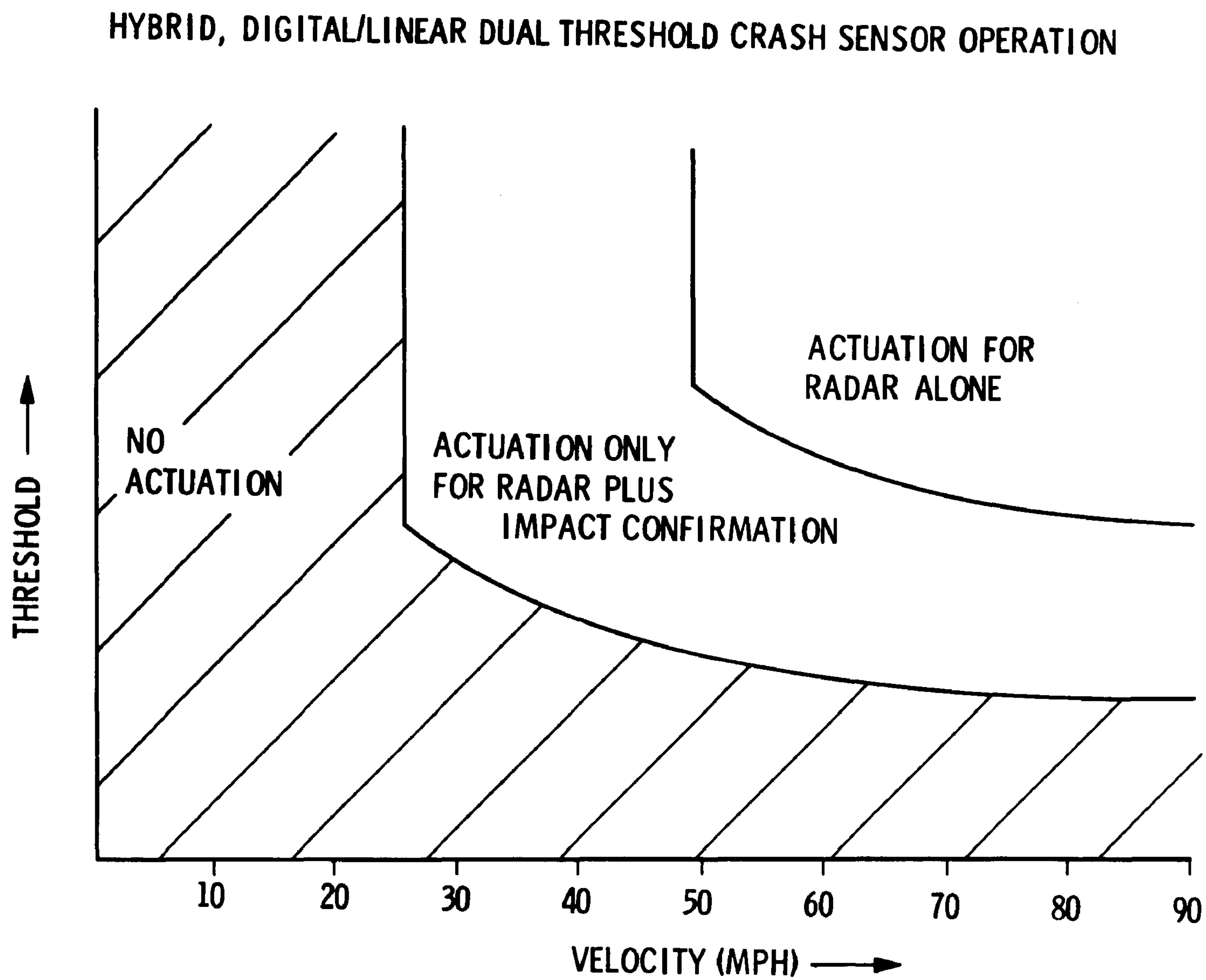


Figure 3-29 Actuation Criteria for Dual Threshold Hybrid Sensor

Figure 3-30 Prototype Radar Crash Sensor - Laboratory Model (10 GHz)

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Figure 3-31a Prototype Radar Crash Sensor - Test Vehicle Installation - Exterior (Antennas Indicated by Arrows)

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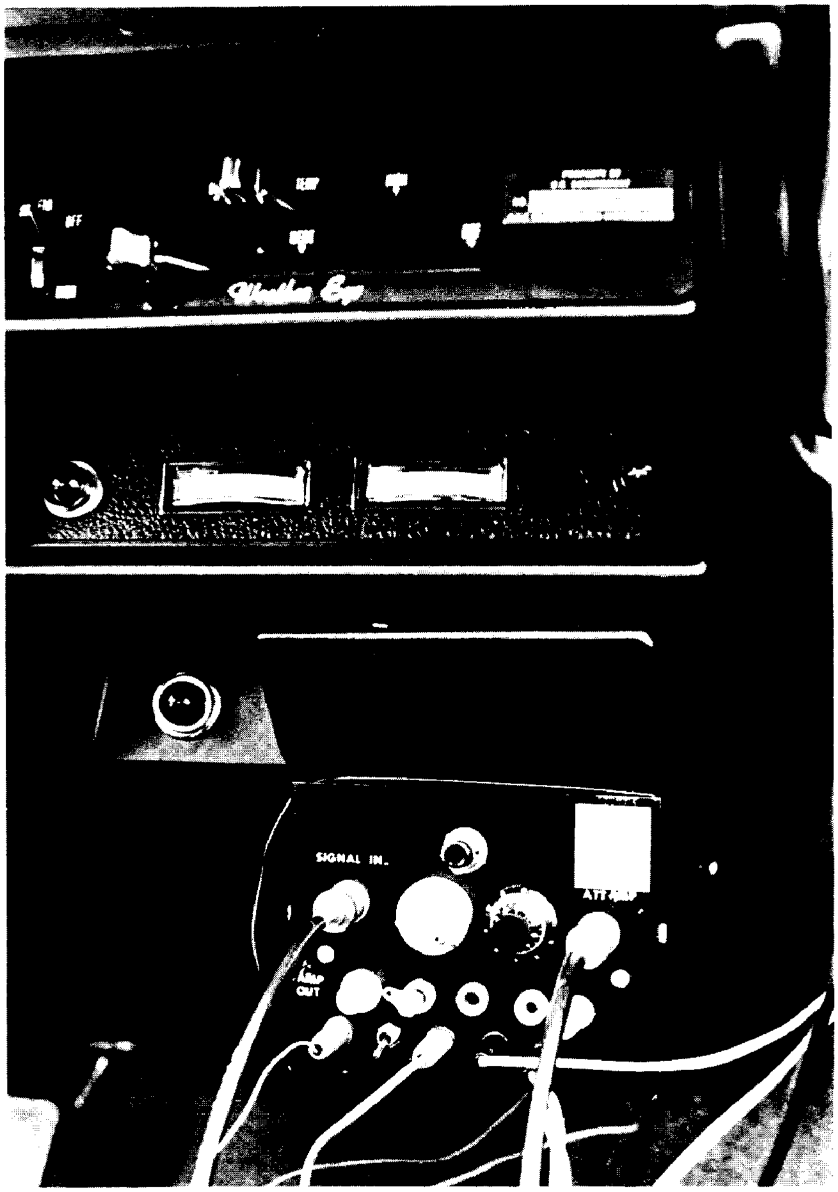

Figure 3-31b Prototype Radar Crash Sensor - Test Vehicle Installation - Interior

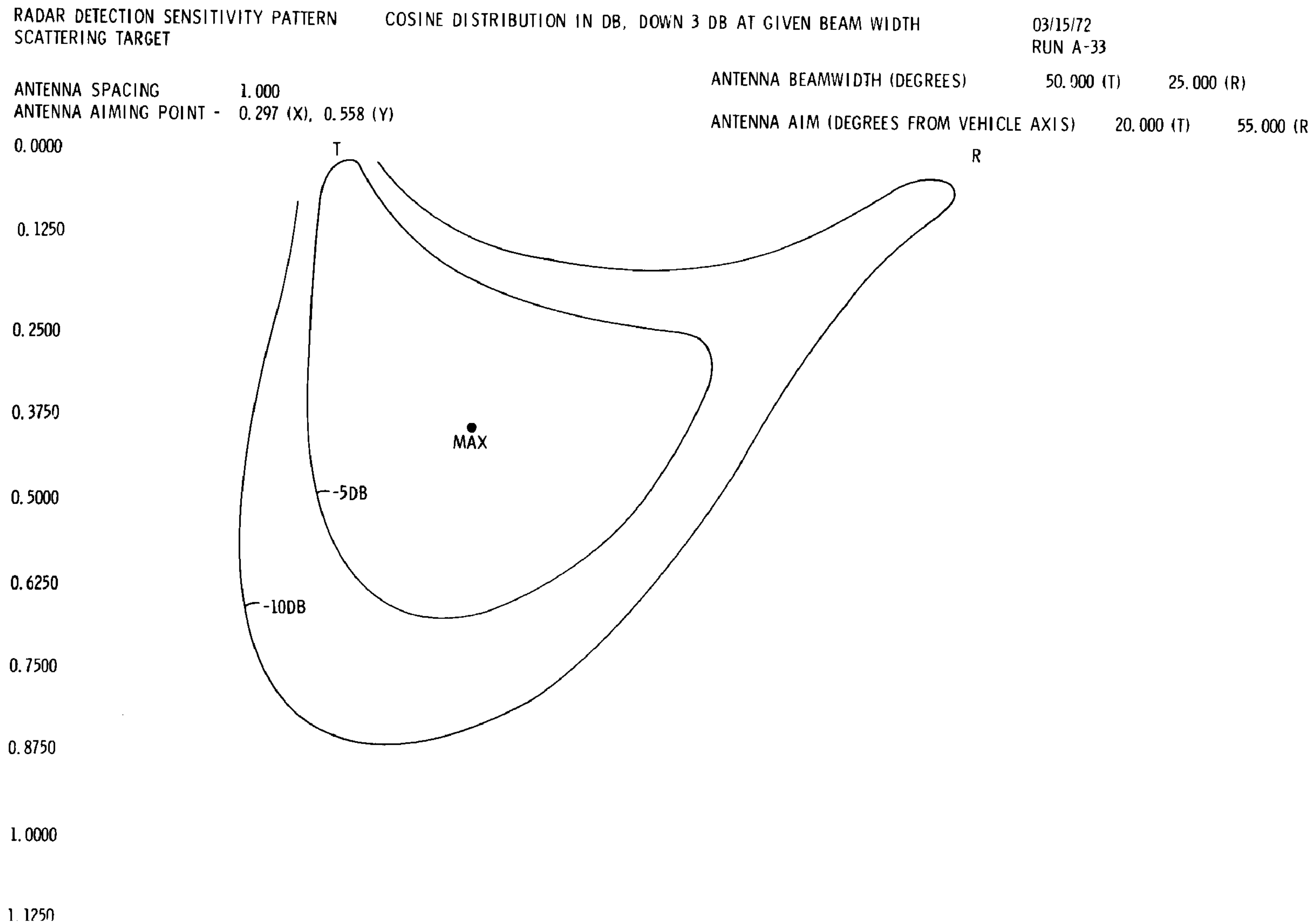

Figure 3-32a Sensitivity Pattern, Skewed System - Calculated

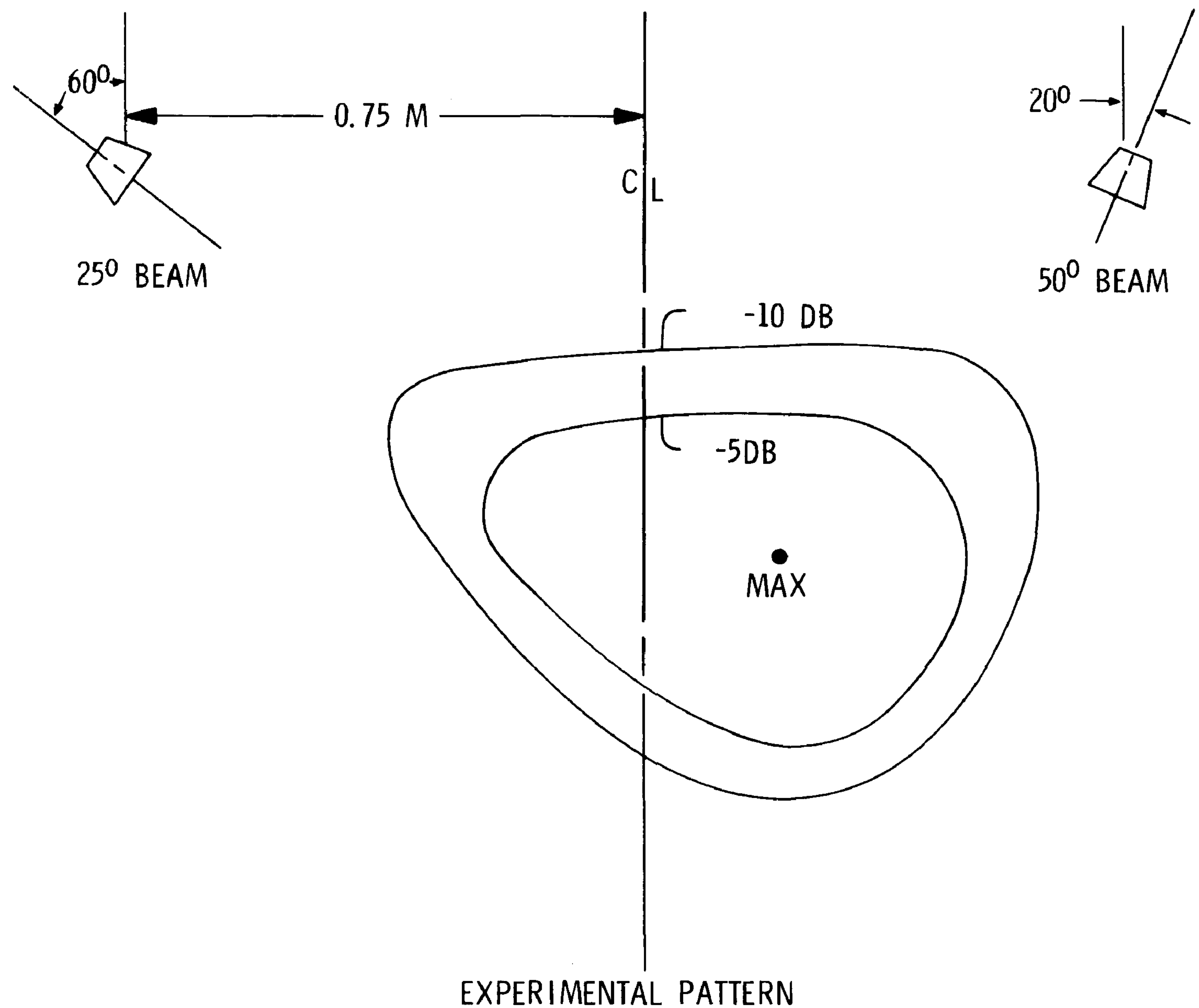

Figure 3-32b Sensitivity Pattern, Skewed System Measured (Skewed in Opposite Direction)

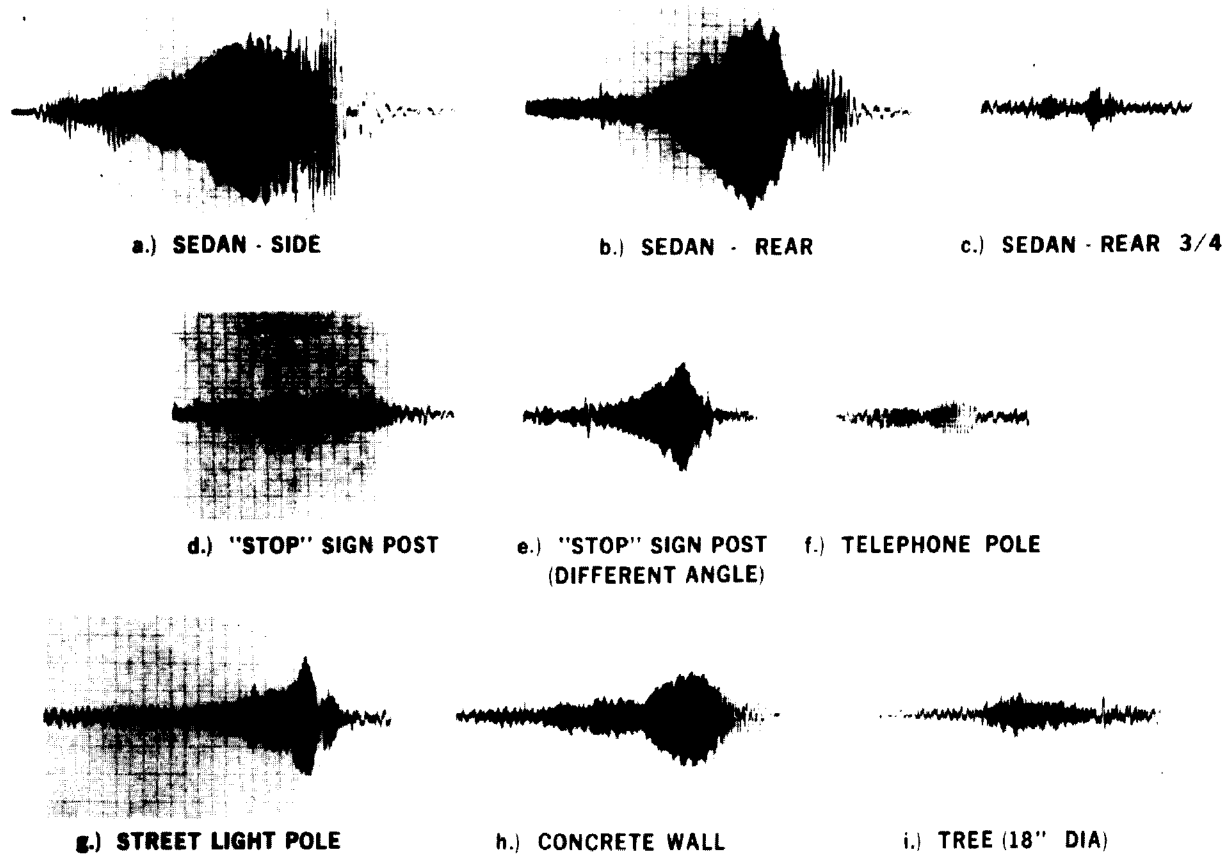

Figure 3-33 Radar Doppler Signatures of Various Targets

range determined entirely by the transducer patterns. Specific considerations relevant to each component were indicated above. Since both operating frequency and propagation velocity are reduced by approximately a factor of 10^6 from the microwave case, the carrier wavelengths-and hence frequencies observed-are quite similar: at 40 kHz the shift is 100 Hz/mph. The signal processing is identical to that described in previously, with the single change that the high pass filter must have a cutoff frequency of approximately 1600 Hz for a 15-mph threshold velocity. (Indeed, the same circuit has been used in testing.)

3.2.1 A Sonar Crash Sensor

The signal source which has been used is merely a simple transistor oscillator operated from 12 VDC. The receiver consists of an amplifier and mixer diode, followed by a low-pass filter to eliminate the 40 kHz carrier. Figure 3-34 shows a block diagram of the acoustic system. The transducers used experimentally are hermetically sealed, although not inherently suited to external mounting without further weatherproofing. Unlike the microwave case, where basically suitable antennas, with appropriate all-weather "windows", are readily obtained, there are few commercial applications, and thus a very limited availability of transducers with appropriate characteristics. There is not a great problem with the transmitting unit, which can be narrow-band, but - as indicated earlier - obtaining the required bandwidth in a sensitive, low-cost receiving transducer is a more difficult task. (The major present market for such

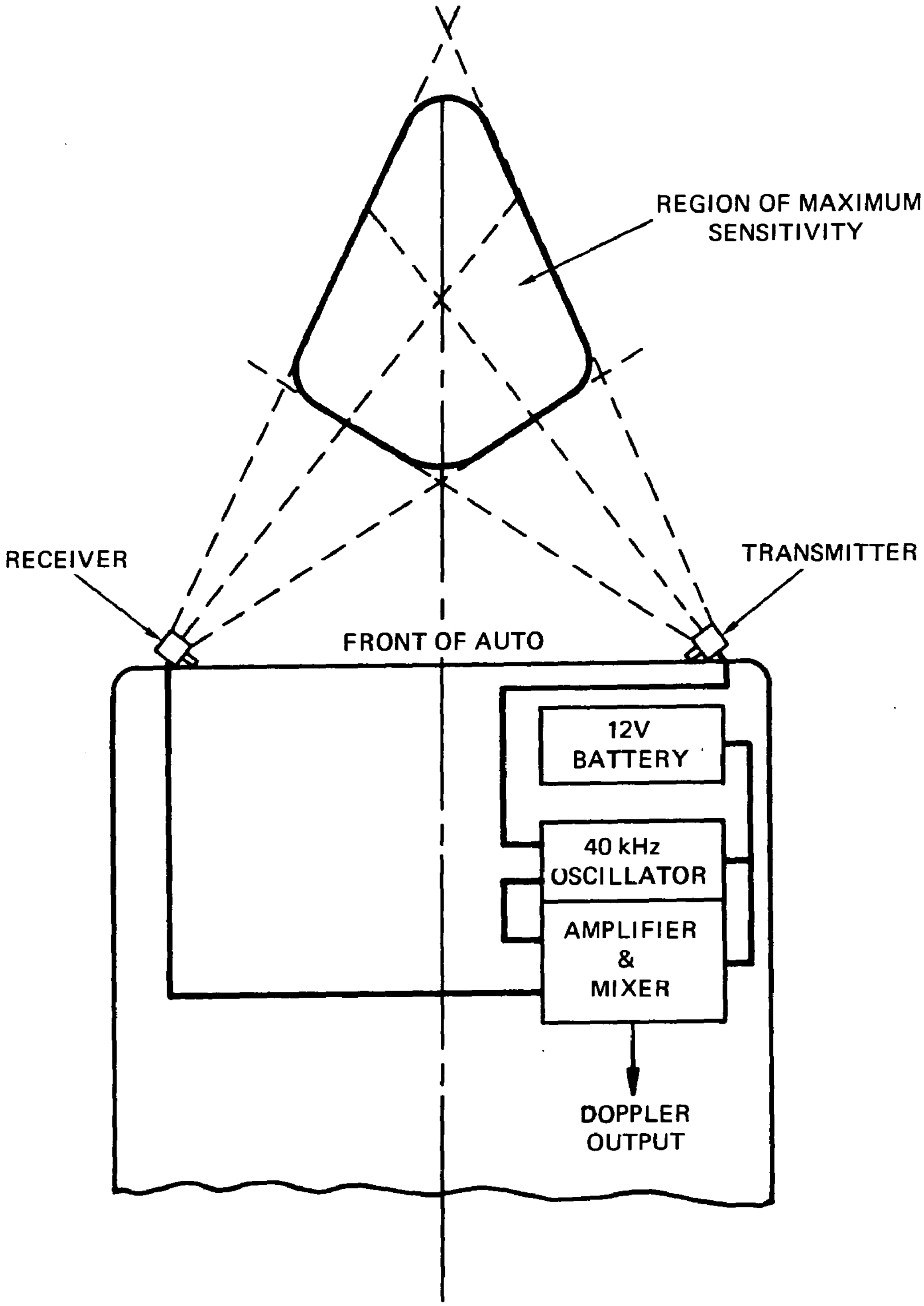

Figure 3-34 Block Diagram of Acoustic (Sonar) Crash Sensor

components is intruder alarm systems, where motions of .1 to 10 mph (10 to 1000 Hz) are of special interest.) However, the low available bandwidths are adequate for the most important class of tests, in which the vehicle is rolled slowly up to various obstacles (with no high-pass filtering for velocity discrimination) for measurements of acoustic reflectivity. It is by this means that various potential targets may be characterized and system effectiveness estimated. Also, a narrow band is sufficient for measurement of environmental noise in the vicinity of 40 kHz.

40 kHz transducers have been obtained which, when hermetically sealed, can achieve substantial bandwidth (10-200) by means of electrical matching circuits, as is generally the case for resonant devices. A useful technique for further study would be selection for use as the transmitting transducer a unit with a resonance frequency approximately 1500 Hz below the low frequency cutoff of a broad-banded receiving transducer. This would provide the required low velocity threshold directly.

Due to the less broadly developed nature of ultrasonic technology in the frequency range of interest, this portion of the TSC program required more emphasis on characterization and improvement of components, particularly transducers. Several types of crystal transducers have been tested. They are small, rugged, and relatively inexpensive, two resonating near 40 KHz (one with a mesh-covered aperture, the other hermetically sealed), and one tuned to 22.5 KHz (hermetically sealed by an aluminum diaphragm). Measurements have been made using identical as transmitter and receiver, mapping the directional propagation characteristics and observing reflections off several different types of surfaces. Attempts have been made to focus the beam with a simple cylindrical horn. Comparison of data taken with and without such a horn showed improvement in this respect. The higher-frequency unit permitted better focusing than the other, as expected. Reflected signals and phase shift (or doppler effect) with motion were studies with smooth surfaces of metal, wood, glass and cardboard. All gave pronounced reflections at several feet at the specular angle, although quantitative reflection coefficients have not been determined.

A prototype system was set up with a transmitter at the center, flanked by two receiving transducers 24-inches on each side tilted inward at an angle 20^{o} off axis. The purpose of this geometry was to create an extended zone of about 40 inches wide, 30 inches in front of the array. However, significant sensitivity was still observed as close at one foot and as far out as six feet. A number of baffle structures have been designed to minimize impact of miscellaneous road debris--pebbles, ice, insects, etc.,--while not interfering with the acoustic behavior. Baffles have been built which show no loss of signal strength and will eliminate direct impacts, although bandwidth has not been measured (being limited by the transducers in use) and the actual road effectiveness remains to be determined. Figures 3-35 thru 3-38 show, respectively, a 40-kHz transducer, the baffle design, a completed unit, and graphs of the transducer pattern with and without baffle.

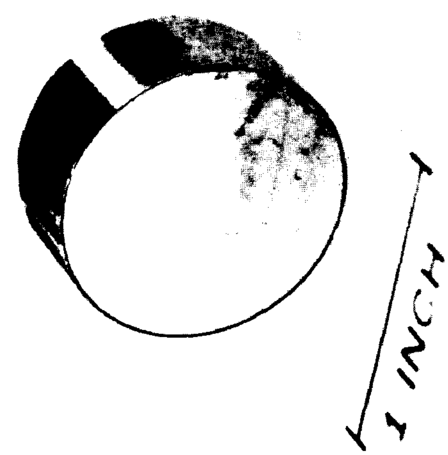

Figure 3-35 Acoustic Transducer

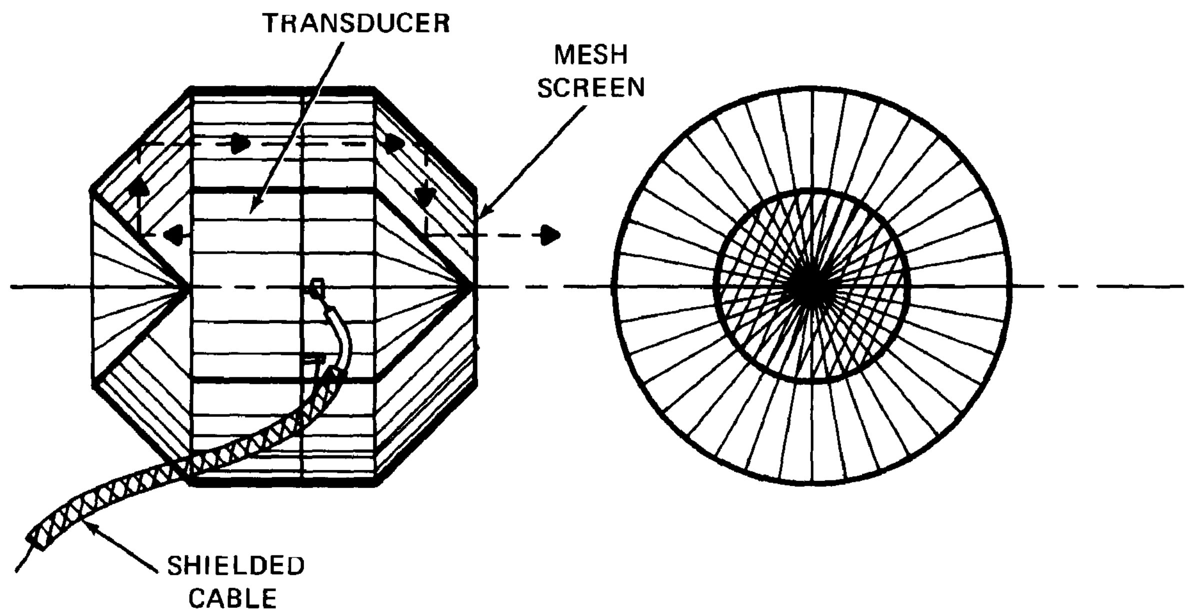

Figure 3-36 Design of Battle for Transducer

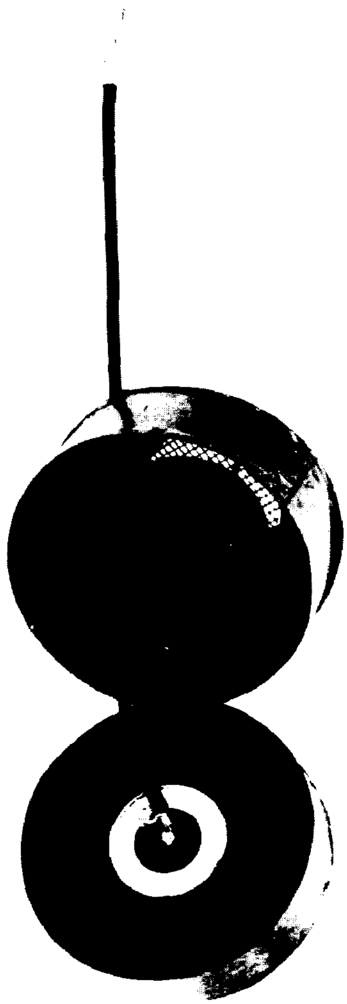

Figure 3-37a Experimental Model of Battle - Open

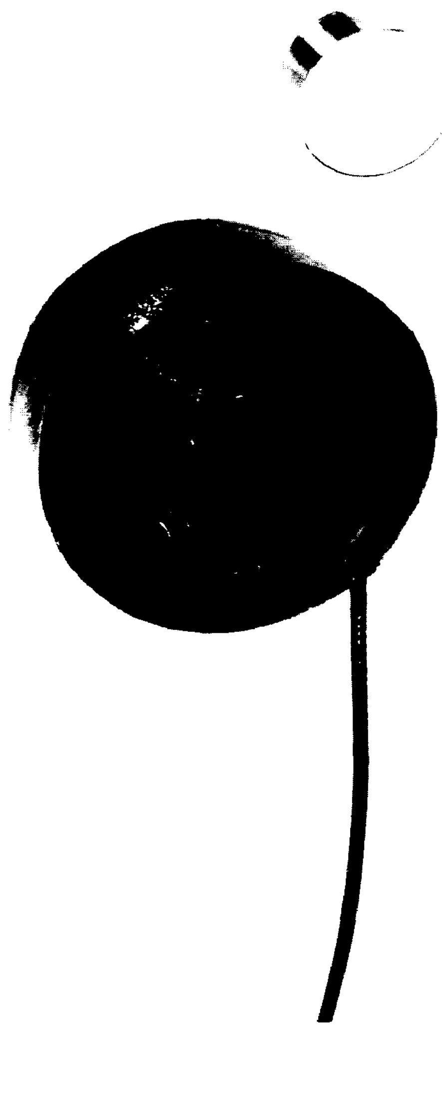

Figure 3-37b Experimental Model of Battle - Assembled

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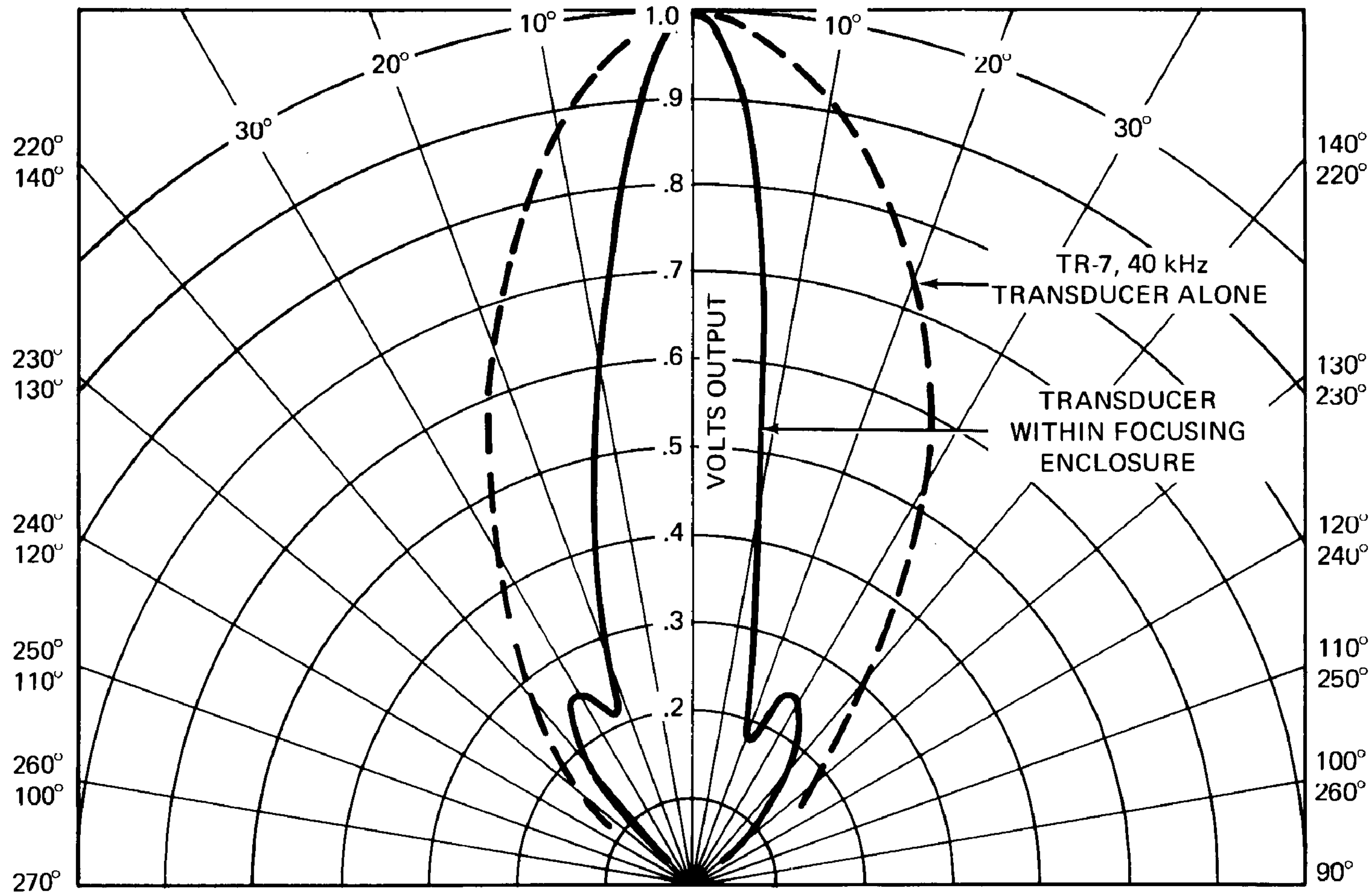

Figure 3-38 Transducer Patterns With and Without Battle

Hardware and procedures described above and in Chapter 4 have been utilized to examine the potential utility of an acoustic (ultrasonic) ranging method. In addition to undergoing laboratory measurements, the system has been mounted on a test vehicle (Figure 3-34) and doppler signatures of a variety of targets were recorded as the car was driven slowly to a point immediately in front of the obstacle in question. Oscillographs of the amplified doppler return for typical obstacles are shown in Figure 3-40. The doppler shift here is approximately 108 Hz per MPH (c = 330 meter/sec; f = 40 KHz), or 3.5 times that for the radar case. Associated with this difference is a propagation wavelength (.8 cm.) shorter by this same factor than was the case for radar. Thus, in addition to the comparison between acoustic and electromagnetic reflectivity, results such as are shown in Figure 3-40 above are partially determined by the dimensions of the targets, including details of surface structure, in terms of radiation wavelength.

The basic observation to be made concerning the results of these measurements is the relatively undiscriminating nature of sonar. Most targets give returns in a fairly narrow range - approximately a factor of two variations. Further, these and other tests show poor discrimination between hazardous obstacles - vehicles, walls, trees, etc. - and relatively innocuous objects - chain-link fence, shrubs, people and animals, etc. This problem is illustrated even more dramatically in Figure 3-41, which shows the response of a pulsed sonar system to a large piece of sheet metal, a piece of paper, a small plastic bag, and a human

Figure 3-39 Prototype Sonar Crash Sensor - Test Vehicle Installation (Transducers Indicated by Arrows)

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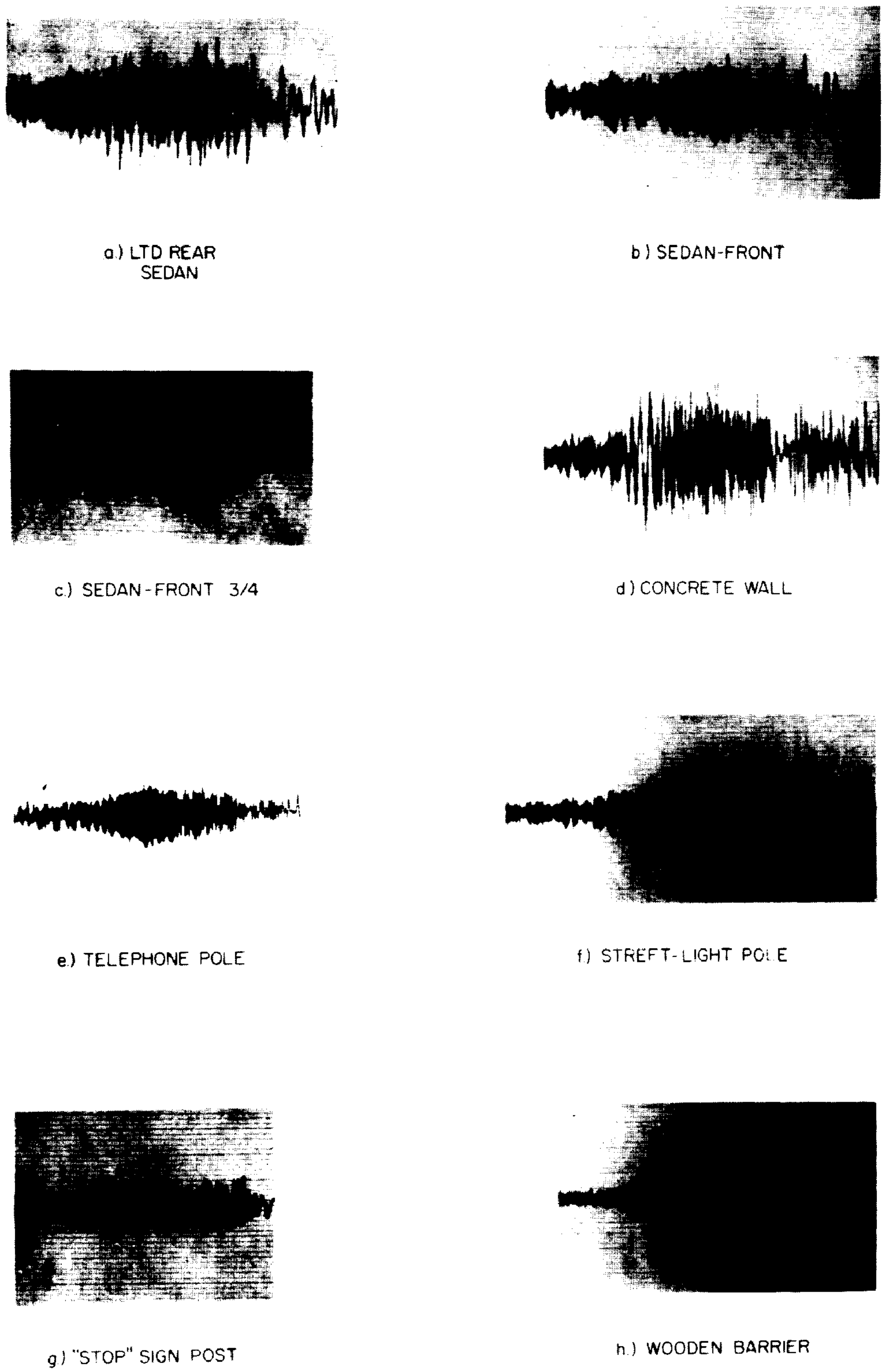
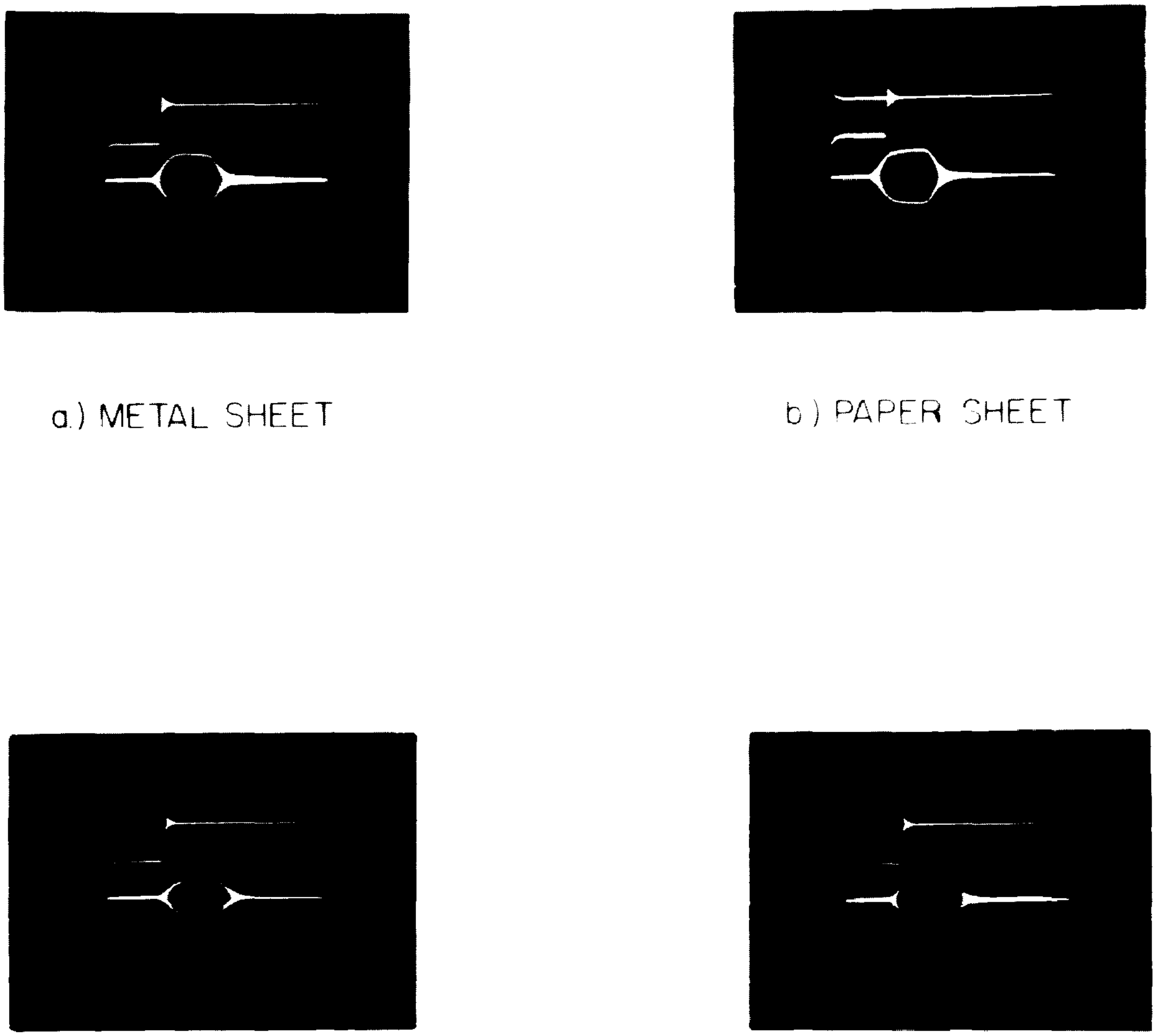


Figure 3-40 Sonar Doppler Signatures of Various Targets



a.) METAL SHEET

b.) PAPER SHEET

c.) HUMAN BODY

d.) PLASTIC

Figure 3-41 Sonar Pulse-Echo Signatures of Various Targets

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being. The potential for inadvertent actuation is clearly very high unless the triggering threshold is so high that the system will seldom operate, even in serious crashes. Thus, the previous findings that indicated sonar not to be promising for anticipatory sensing are confirmed.

4. MICROWAVE CHARACTERISTICS OF POTENTIAL COLLISION OBJECTS

4.1 INTRODUCTION

One central aspect of the ultimate practicality of a microwave crash sensor is its ability to correctly detect "true" targets--objects in the automobile's path that present a threat to the occupant's safety--while simultaneously not responding to "false-alarm targets"--objects that are not an actual threat. As discussed elsewhere in this report, complete accuracy in object discrimination is impossible to achieve; therefore, in order to realize a system whose overall operation is nearly optimal, mechanical *and* microwave information should be used when possible. The issue discussed in this chapter is the quality of the microwave information about targets. From a systems standpoint, this question is an important one, since it is the microwave information that is first obtained about a target. Furthermore, under certain conditions (very high speeds), microwave information alone must be relied upon for the restraint deployment decision.

The subject of microwave characteristics of targets is discussed here from the viewpoint of electromagnetic theory, and from the perspective gained from an extensive laboratory and field experimental program. The microwave characteristics of many true and false-alarm targets are given, as a function of frequency. The capabilities of the microwave sensor to differentiate between true and false-alarm targets are discussed, as is the question of optimal microwave frequency, considered in terms of target discrimination.

Three operating frequencies, 10, 22, and 35 GHz, were used throughout this work. These frequencies cover the range over which simple and relatively inexpensive Gunn diode microwave sources are readily available, antennas are not too large, and dimensional tolerances are not prohibitively severe for possible mass production. Since hardware costs rise sharply with frequency because of dimensional tolerance considerations within both semiconductor device itself and the microwave circuitry, it is desirable to operate at the lowest frequency compatible with operational accuracy.

4.2 ELECTROMAGNETIC THEORY

In traditional doppler radar applications, the microwave wavefronts incident on a target can be considered as plane waves. These waves are partially scattered by the target, giving rise to scattered-wave wavefronts which, by the time they are received by the radar, are once again plane waves. This theoretical plane-wave picture cannot be used exactly in analyzing the microwave crash sensor behavior, since for this case one is generally dealing with targets that do not lie within the far-field region of the antennas. The far-field region of an antenna begins at a distance $L = \frac{2D^2}{\lambda}$ from the antenna, where D is the diameter of the antenna aperature and λ is the wavelength.[7] Since the 10 GHz microwave crash sensor uses antennas with aperature D = 10 cm, and employs microwaves of wavelength 3 cm, the distance to the far-field region is L = 70 cm. Targets lying closer this to the automobile are often considered.

The spatial patterns and intensities of plane EM waves scattered from spheres, cylinders, thin metal disks, and other objects have been studies extensively,[8,9] but the results do not apply exactly to any real targets, most of which are irregular, and which scatter waves that are not planar. However, exact theories do serve as a guide as to what to expect in various circumstances, and that is how the theoretical considerations were used in this study. It is known that surfaces with roughness in which irregularities in the surface have dimensions large compared to a wavelength tend to scatter incident EM radiation randomly in all directions. Surfaces for which the irregularities are small compared to a wavelength tend to reflect waves as does a good mirror i.e., plane waves are reflected from a smooth flat surface as plane waves, and the angle of incidence equals the angle of departure. A small scattering object placed in the path of an incident plane wave creates a scattered wave whose properties are the same as a wave emanating from an aperature the size and shape of the scattering object.[10] Thus there can be lobes and nulls in the angular pattern of scattered radiation, just as there are in antenna patterns. Objects made of material having dielectric properties not too different from free space are poor scatterers, whereas metallic objects are perfect scatterers since all incident radiation is scattered in some direction. For objects quite small compared to a wavelength, diffraction theory predicts that the scattered radiation will be directed in all directions, with no nulls.[11]

When all of these theoretical factors are taken into account, one can predict that the sides of automobiles and concrete abutt-ments with smooth surfaces would produce very large doppler signals, whereas the rough surfaces of trees would produce smaller doppler signals. And other objects large or small, with regular or irregular surfaces, made of wood or metal or other materials, should produce some doppler signals with amplitudes very difficult to calculate, but easy to measure and understand.

4.3 REFLECTIVE PROPERTIES OF MATERIALS

In order to gain information on expected amplitudes of scattered waves as a function of target composition, the experiment depicted in Figure 4-1 was performed, in which microwaves were reflected off various surfaces, and the reflected power measured. The frequencies employed were 10, 22, and 35 GHz. The results for reflectance obtained are given in Table 4-1. The system was calibrated by use of a flat aluminum sheet which was assumed to have perfect reflectance. Then, other targets were substituted at exactly the same position that the metal sheet had occupied. All the surfaces were nominally "flat" (planar); however, the concrete block did have surface roughness. This surface roughness could be expected to produce more diffuse scattering and correspondingly less specular reflection as the frequency increases, thus accounting for the decreased reflectance as measured by this procedure at higher frequencies. When the surface of the concrete block was soaked with water, the

TABLE 4-1 REFLECTIVITY OF VARIOUS MATERIALS (ALL SURFACES "FLAT")

	10GHZ	22GHZ	35GHZ
METAL SHEET	0 DB	0 DB	0 DB
FLAT SECTION OF WET TREE	-1	-1	-2
WET CONCRETE BLOCK	-2	-2	-3
DRY CONCRETE BLOCK	-3	-5	-8
DRY PINE BOARD, WET SURFACE	-4	-4	-4
DRY PINE BOARD, DRY SURFACE	-7	-7	-12
METAL STRIP, 2 1/2" PERFORATED	-1	-1 1/2	-2

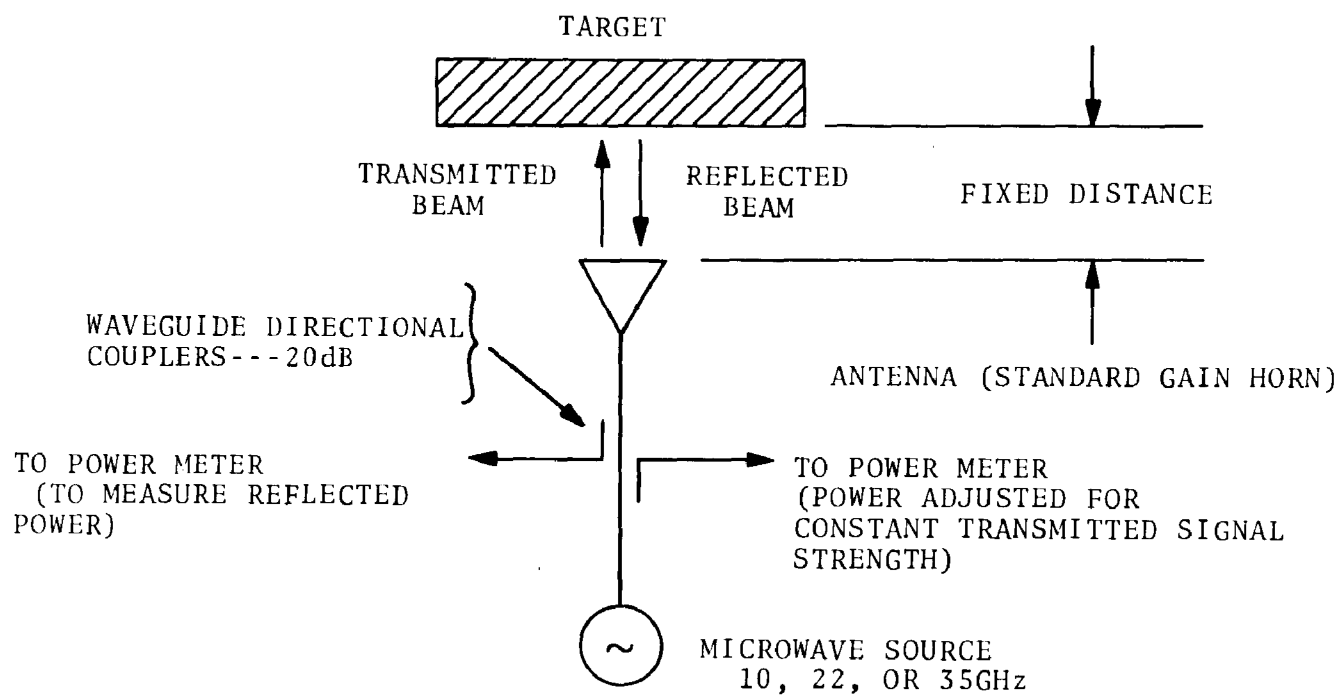

Figure 4-1 Reflectance Measurement System

small voids in the surface were filled in and the surface made more smooth and less porous. The result was an increase in reflectance, especially at the highest frequency where it had been most degraded before.

The effect of surface wetness is most dramatically seen in the case of the pine board. The dry pine did not represent too great a dielectric mismatch with free space, but when the surface was wetted, reflectance increased from two to six times, depending on frequency. Since water has a relative dielectric constant of 81, compared to the figure of approximately 2.5 for soft wood,[12] an air-water interface has a reflectance of[13]

$$R = \left| \frac{\sqrt{\epsilon_r} - 1}{\sqrt{\epsilon_r} + 1} \right|^2 = 0.64, = -2 \text{ db}.$$

whereas the corresponding figure for an air-wood interface is R = 0.05 = -13 db. Thus surface wetness, and probably water content, can be overriding factors in determining reflectance of some objects.

4.4 DOPPLER SIGNALS PRODUCED BY VARIOUS OBJECTS

Figure 4-2 shows the three-frequency crash sensor radar system used to make the measurements described in this section. Each channel of this system is essentailly a cw homodyne bistatic doppler radar of the type described in Chapter 3. The 10 GHz channel has exactly the same microwave characteristics as the

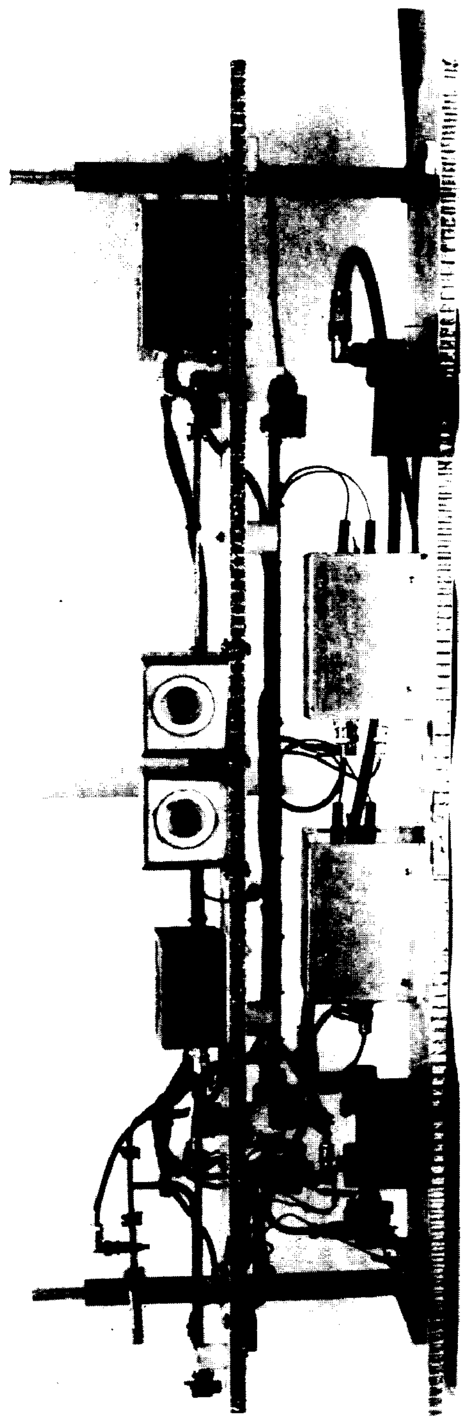

Figure 4-2 Three-Frequency Measurement System in Laboratory

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system permanently mounted in the test automobile. The two higher frequency channels use antennas correspondingly smaller and with approximately the same antenna patterns as the 10 GHz channel. The doppler signals were directly recorded instead of being processed in any other way. Figure 4-3 shows the system mounted on the front of the automobile for making field tests, and Figure 4-4 shows a block diagram of the complete system.

When the three-frequency system was used in the laboratory, it was positioned on a bench, and targets were moved in and out by hand in front of it while the three doppler signals were recorded. During field tests with the system mounted on the front of the automobile, the automobile was driven very slowly up to and away from targets. The very low lower cutoff frequencies of the doppler signal amplifiers, approximately 3 Hz, coupled with the dc recording capability of the FM tape recorder made it possible to perform these tests at low speeds in a safe and reproducible manner. The doppler signals that were tape recorded were played back, displayed on an oscilloscope, and photographed. The fourth channel of the tape recorder was used in the standard AM mode for voice narrative of the measurements in progress. Amplifier gains of the crash sensor system and of the tape recorder channels were adjusted as closely as possible to give equal-amplitude oscilloscope pictures from the three channels for the "calibration" target, which was a 15" x 18" aluminum sheet.

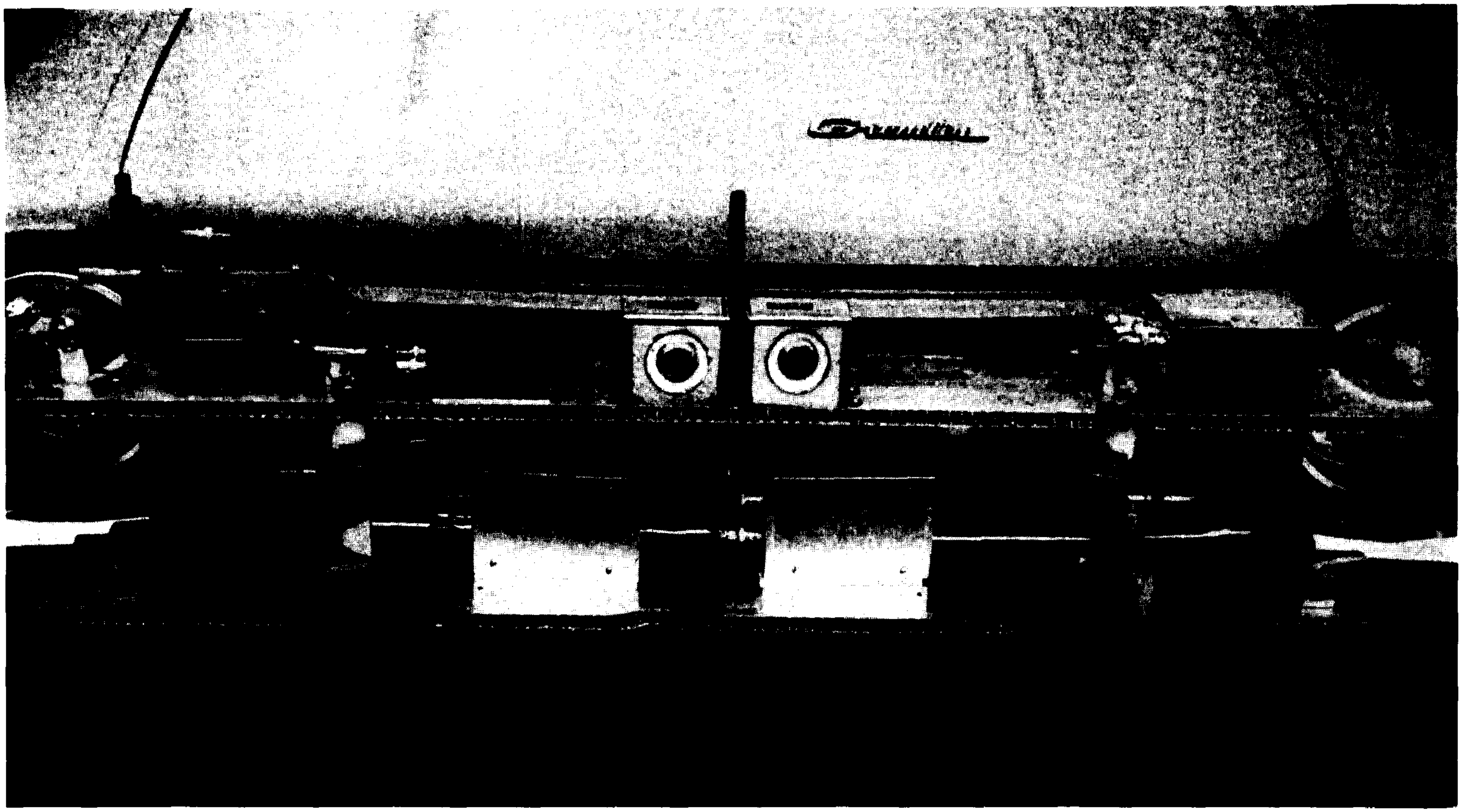


Figure 4-3 Three-Frequency Measurement System Mounted on Test Vehicle

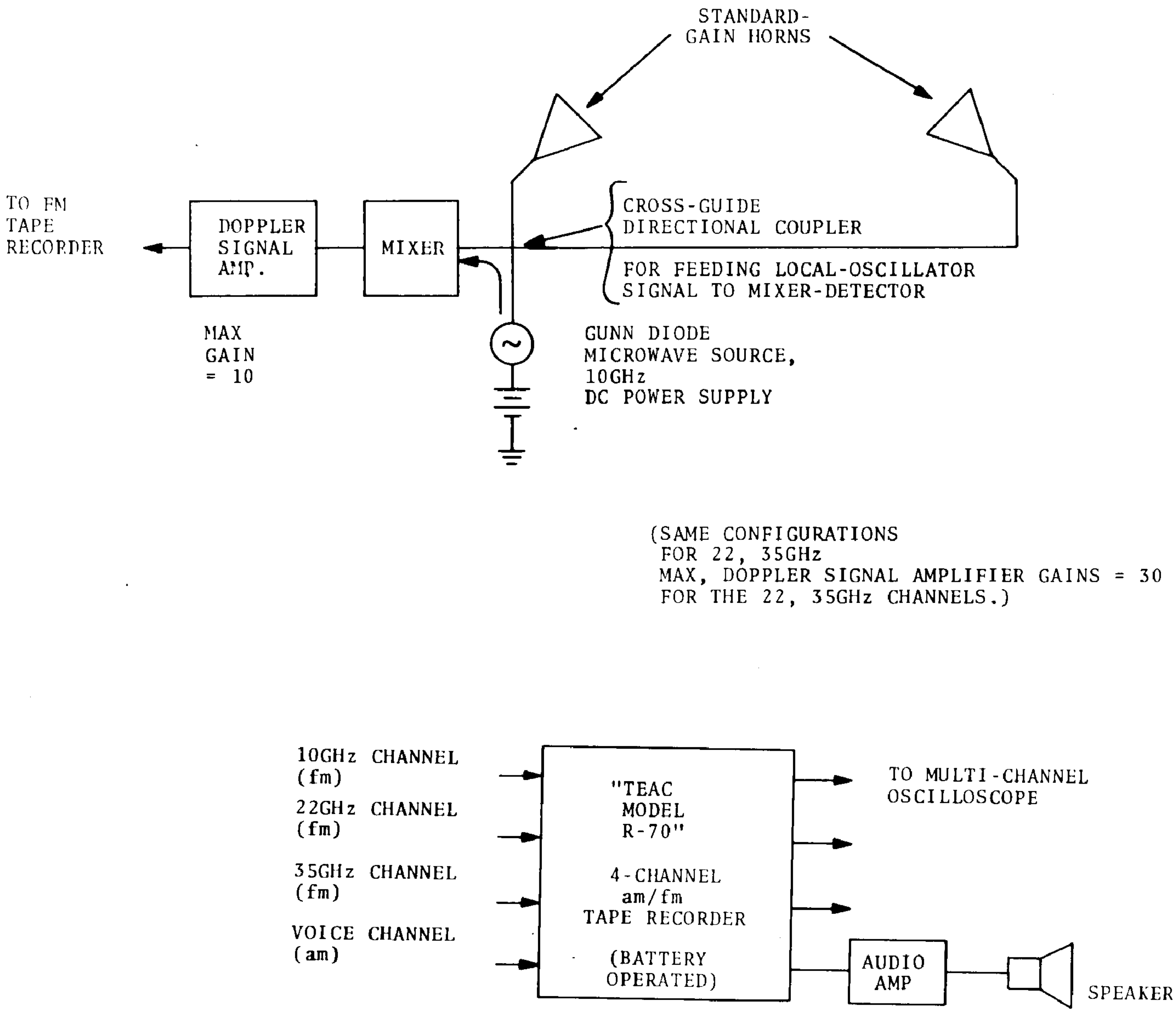


Figure 4-4 Block Diagram of the Three-Frequency Measurement System

Since the homodyne cw doppler detection technique employed in each microwave channel uses a local oscillator signal that is mixed with the doppler-shifted microwave signal, the detection process is essentailly one of linear detection. That is, the doppler signal out of the mixer is directly proportional in amplitude to the amplitude of the detected microwave signal from the target.[14] The doppler signal amplitude is translated to relative microwave power in the signal received from the target by the relationship $W_{db} = 20 \log_{10}(V/V_{reference})$, where V is the envelope amplitude of doppler signals displayed on the oscilloscope.

Figure 4-5 shows the oscilloscope photos of the recorded doppler signals for many of the targets investigated in this study. All amplitudes for signals in the three microwave channels were referenced to the signals produced by the aluminum sheet, and these are given for each target for the three frequencies used. Note that the vertical voltage scales differ from picture to picture.

Targets that represent the greatest threats in collisions are the first discussed. Figure 4-5b shows that the broad, relatively flat surface of the back of a panel truck provides doppler signals barely smaller than the flat metal sheet. The slight difference is attributed to undulations in the surface of the truck, but the difference in amplitudes between the sheet and the truck is negligible. Figure 4-5c shows that the reflections received from a more irregular metal surface are still smaller in amplitude, as is expected from theory. The reflected signal

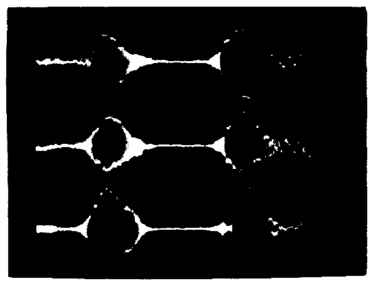
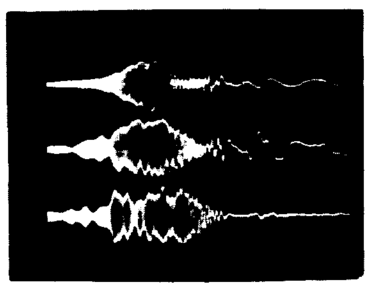
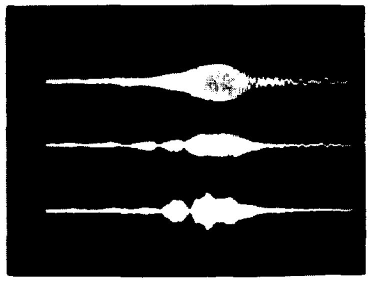
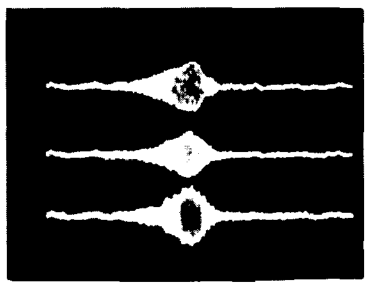
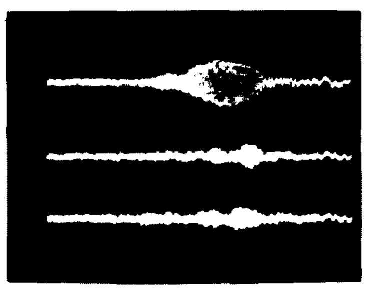
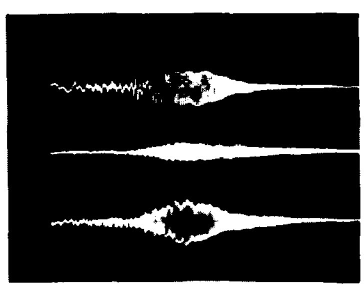
FIGURE	TARGET	SCALES: SEC/DIV. VOLTS/DIV.	"OSCILLOSCOPE TRACES"	MAX. SIGNAL STRENGTH WITH RESPECT TO SIGNALS FROM REFERENCE TARGET, GIVEN IN dB 10GHz	22GHz	35GHz
a	15"x18" FLAT AL SHEET	→ 0.2 ↕ 2.0		0	0	0
b	REAR OF PANEL TRUCK	→ 0.2 ↕ 2.0		-2	-1	-1
c	PLASTIC GRILLE OF AMC GREMLIN COVERED WITH AMUMINUM FOIL TO SIMULATE METAL GRILLE	→ 0.2 ↕ 1.0		-5	-4	-2

Figure 4-5a,b,c. Recorded Doppler Signals from Various Targets, Obtained at 10, 22, and 35 GHz, with Maximum Amplitudes Reference to Signal Amplitudes Produced by Standard Calibration Target from the automobile grille is within 6 db of that of the flat sheet. The cement bulkhead of Figure 4-5d produced reflected signals of the same approximate amplitude as the automobile grille. The wooden telephone pole of Figure 4-5e is seen to produce signals significantly reduced in amplitude, due to the relatively small dielectric mismatch present at the air-wood interface discussed previously. The doppler signals produced by the tree, shown in Figure 4-5f, are further reduced in amplitude by the random scattering effects of the rough (bark) surface of the tree. The effects of surface roughness are more pronounced at the highest microwave frequency and corresponding shortest microwave wavelength. Obviously, in order reliably to detect trees, the system sensitivity would have to be great enough to detect and act on signals about 20 db less than the signals procuced by a flat metal surface.

The targets discussed next are ones that represent a lesser threat than those described in the previous paragraph, due to the fact that they are much less solid objects. However, collisions with these objects do represent danger. The doppler signals from a 55-gallon drum shown in Figure 4-5g are seen to be approximately the same amplitude as those from the automobile grille. The doppler signals produced by the fire hydrant are seen in Figure 4-5h to be considerably smaller, due to the smaller size and quite irregular surface of the hydrant. In fact, the signals produced by the 3-1/4" metal pole, which was considerably smaller in crosssection than the hydrant but had a perfectly smooth cylindrical surface, are observed in Figure 4-5i to be of essentially the same

d	SMOOTH-SURFACED CEMENT BULKHEAD	→ 0.2 ↕ 2.0		-6	-16*	-6
e	TELEPHONE POLE APPX. 12" DIAMETER	→ 0.2 ↕ 0.5		-14	-14	-13
f	TREE, APPX. 18" DIAMETER, WITH ROUGH BARK SURFACE	→ 0.2 ↕ 0.5		-15	-19	-20
g	55 GALLON STEEL DRUM	→ 0.2 ↕ 2.0		-6	-14*	-4

*PROBABLE EQUIPMENT MALFUNCTION

Figure 4-5d,e,f,g. Recorded Doppler Signals (Cont.)

amplitude. Figure 4-5j shows that the 6" square concrete post produces doppler signals that are slightly larger than those produced by the 3-1/4" metal pole when the automobile approaches the pole in a direction normal to the pole's flat side. However, when the direction of approach is 30° from the normal, the signals are considerably less. There is still some received signal, due to the finite angular width of the "main lobe" of the scattered wave. But, as Figure 4-5k shows, the portion of the signal that it diffracted toward the receiving antenna, rather than being specularly reflected away from it, diminishes rapidly as microwave frequency increases and wavelength decreases. This behavior is analogous to the fact that an aperature-type antenna produces an radiation pattern whose main lobe width decreases as wavelength decreases, thus concentrating the radiated energy more in one direction. Thus, if one wishes to detect objects such as square concrete posts in as uniform a manner as possible, independent of direction of approach, the lower frequency is to be preferred.

The next series of targets to be discussed are ones that represent no threat in themselves, but if struck (especially at very high speeds) might indicate that an automobile was likely to collide with something worse. The 1-1/2" wide surface of the top of the "t" of a length of "T"-iron is seen in Figure 4-5l to produce doppler signals larger than those of the tree. This illustrates the existence of a target discrimination problem best dealt with by incorporating mechanical information concerning

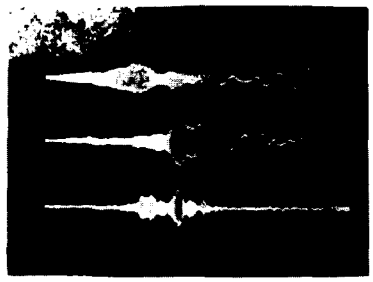
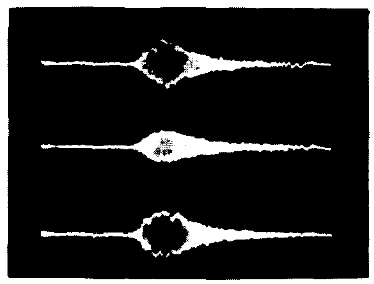
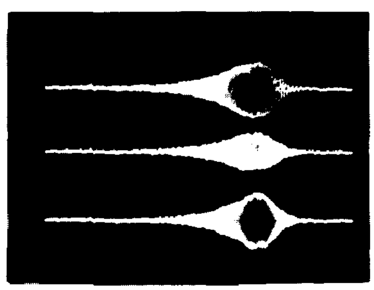
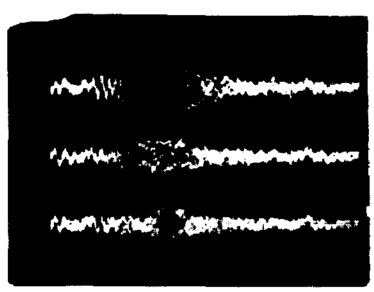
h	FIRE HYDRANT	→ 0.2 ↕ 1.0		-12	-7	-10
i	METAL POLE, 3 1/4" DIAMETER	→ 0.2 ↕ 1.0		-9	-11	-10
j	CONCRETE POST, 6" SQUARE, APPROACHED NORMAL TO ONE FACE	→ 0.2 ↕ 1.0		-8	-10	-7
k	SAME POST APPROACHED AT ANGLE OF 30^0 TO NORMAL	→ 0.2 ↕ 0.2		-19	-23	-24

Figure 4-5h,i,j,k. Recorded Doppler Signals (Cont.)

targets when assesing target threat, especially at lower speeds when the time is available. Even the board face of a 2" x 4" wooden beam can produce doppler signals larger than those of a tree, as can be seen in Figure 4-5m, due to the fact that the tree is rough and the beam is smooth. Even the narrow face of the wooden beam produces doppler signals larger than those from the tree at the highest frequency, where the difference in surface texture matters most, as is seen in Figure 4-5n. This figure also illustrates the lobed nature of the radiation pattern from a narrow planar source. As the automobile moves closer to the beam and the angle from the two-by-four to the receiving antenna changes, the receiving antenna successively passes through lobes and nulls of the scattered radiation pattern. The number of lobes is seen to be greater at shorter wavelengths, as theory predicts. This type of pattern is theoretically elegant, but is of little practical importance, as it depends strongly on target size and orientation. In Figure 4-5o, it is seen that even dense bushes provide detectible doppler signals that are not dramatically smaller than those of the tree. The received signal from a target as diffuse as a bush must be regarded as the algebraic sum of individual signals of very small amplitude from various parts of the bush; since these individual signals have random phases with respect to each other, their powers add. (It is probably the case that the denser the bush, the greater the total received doppler signal.)

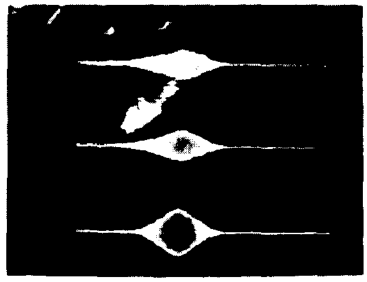
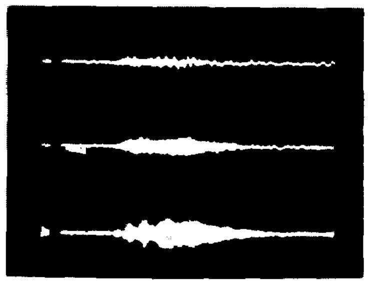
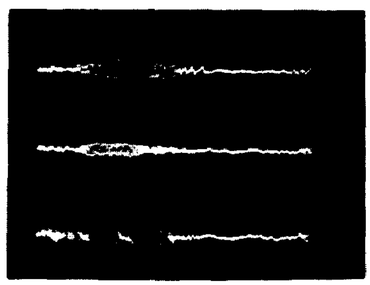
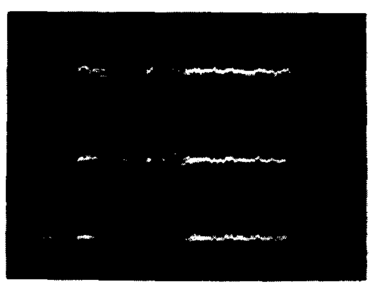
l	1 1/2" x 1" T-IRON, LOOKING AT 1 1/2"-WIDE TOP OF T	→ 0.2 ↕ 2.0		-13	-11	-6
m	SAME T-IRON LOOKING AT EDGE OF WEB	→ 0.2 ↕ 1.0		-20	-16	-14
n	WOOD 2x4, BROAD FACE	→ 0.2 ↕ 1.0		-14	-19	-14
o	WOOD 2x4, NARROW FACE	→ 0.2 ↕ 0.5		-18	-17	-15

Figure 4-51,m,n,o. Recorded Doppler Signals (Cont.)

The final category of targets to be considered are targets that represent potential false-alarm and vandalism problems and no real threat whatsoever. The targets chosen for this study consisted of wet and dry paper. Paper has a relative dielectric constant in the range of 2.0 to 2.5, and corresponding reflectance in the range 0.03 to 0.05, or -15 to -13 db. As can be seen in Figure 4-5p, 40 sheets thick of 1/2-page size newspaper produces the same doppler signal as the tree at 10 GHz, and a significantly greater signal at higher frequencies. The newspaper must be regarded as a dielectric slab, and theory predicts that dielectric slabs that are thin with respect to the wavelength are much less reflective than thicker slabs. As can be seen from Figure 4-5q, the reflectance of the single-thickness brown paper sack was genuinely negligible when the sack was dry. Wet paper has a greatly enhanced reflectance due to the reflective properties of the water, as can be seen in Figures 4-5r, s. Wet newspaper, four sheets thick, is virtually as good a reflector as a metal sheet, and the wet brown bag produces a doppler signal not very much less. It appears that as far as dry paper is concerned, the lower frequencies are best. One may assume that wet paper will not blow around of its own accord.

As can be seen from Figures 4-5t, u and v, the doppler signals from smooth or rough road surfaces appear to be so much smaller than the signals which must be detected (weaker by approximately 20 dB) that these returns represent no systems problem. Additional doppler signatures of targets made in preliminary

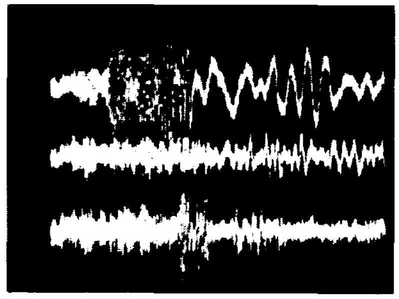
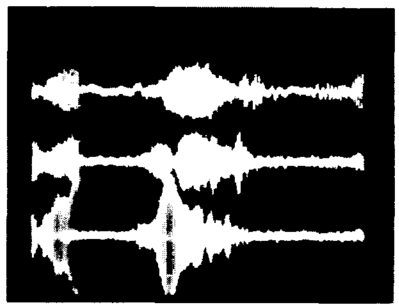
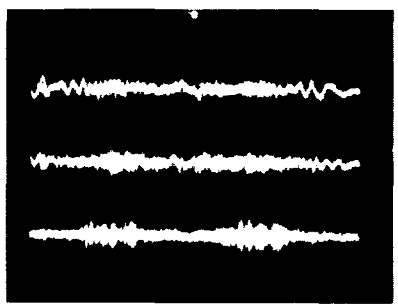
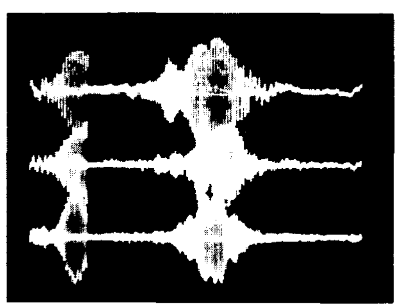
p	BUSHES	→ 0.2 ↕ 0.2		-18	-22	-18
q	40 SHEETS THICK, DRY NEW YORK TIMES, HALF-PAGE SIZE	→ 0.2 ↕ 0.5		-15	-13	-7
r	7" x 14" SURFACE OF DRY BROWN PAPER BAG	→ 0.2 ↕ 0.5		-26	-22	-21
s	4 SHEETS THICK, WET NEW YORK TIMES, HALF-PAGE SIZE	→ 0.2 ↕ 1.0		-2	-3	-4

Figure 4-5p,q,r,s. Recorded Doppler Signal (Cont.)

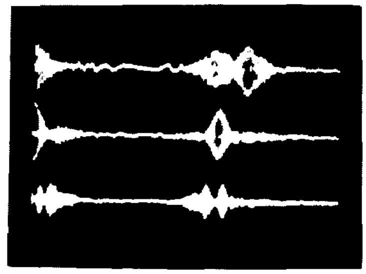
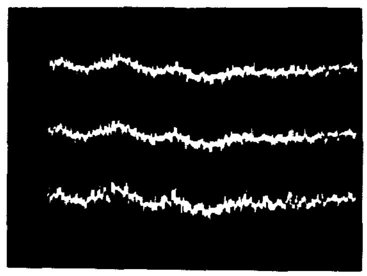
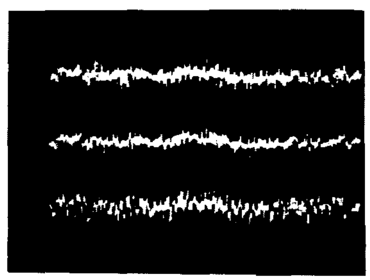
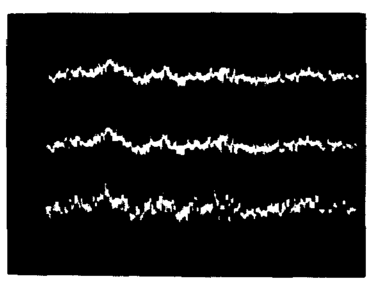
t	7" x 14" SURFACE OF WET BROWN BAG	→ 0.2 ↕ 1.0		-9	-7	-12
u	DRIVING OVER SMOOTH PAVEMENT AT APPX. 35 MPH	→ 0.02 ↕ 0.2		-34	-33	-32
v	DRIVING OVER CORRUGATED METAL SURFACE OF BRIDGE AT APPX. 35 MPH	→ .02 ↕ 0.2		-30	-33	-30
w	DRIVING OVER BRICK PAVEMENT AT APPX. 35 MPH	→ .02 ↕ 0.2		-34	-33	-30

Figure 4-5t,u,v,w. Recorded Doppler Signal (Cont.)

measurements at 10 GHz only were shown earlier in Figure 3-33. There, all signals are presented at the same scale factors, so that direct comparison of amplitude can be made.

4.5 CONCLUSIONS

There is a true-target vs. false-alarm-target discrimination problem arising from the fact that very large objects such as trees, which represent a great threat in event of collision, have surface texture and composition that tends to diminish their microwave reflectance. At the other extreme, objects as innocuous as wet newspapers have very large microwave reflectances. Thus, it appears impossible to use microwave techniques alone to discriminate with complete accuracy between true and false threats.

However, consideration of the results explicitly noted here, as well as of numerous other measurements carried out in the course of this study, in terms of actual collision frequency leads to a relatively favorable conclusion concerning radar anticipatory sensing. This topic is addressed in greater detail in Chapter 6, but it is appropriate to note here that side, front, and rear approaches to automobiles, concrete walls, and large metal poles - well over half of the more serious road or roadside collision objects - should readily be detected in most cases. Telephone poles, and 3/4-approaches to automobiles comprise the most serious deficiency of the system, but two points should be noted. First, they form a relatively small fraction of actual collision objects. Second, trees and telephone poles are typically well off the road, and in many cases one can hope that true impact velocity will be substantially reduced prior to collision. Finally, the 3/4-approach to automobiles undoubtedly includes many accidents, but it does typically lead to a moderately "soft" collision, with a substantial amount of crush in the struck vehicle. Thus, the barrier equivalent velocity can be fairly low.

The target discrimination problem is directly related to the electromagnetic characteristics of the materials involved. One can expect that this difficulty will arise in any other type of system that uses electromagnetic means for detecting targets, as in other proposed cw radar systems[4,5] or pulse systems.[3]

Analysis of the reflective characteristics of potential true and false-alarm targets as a function of frequency indicates that a microwave frequency of 10 GHz is probably to be preferred over a higher frequency. It so happens that economic factors also support this choice of frequency. Problems such as frequency allocation might indicate choice of a higher operating frequency.

5. SUBSYSTEM COST/RELIABILITY CONSIDERATIONS

5.1 INTRODUCTION

As indicated previously, cost imposes one of the more severe constraints upon system development. It has, therefore, been deemed appropriate to give special consideration to estimation of the potential OEM cost of the various elements of a radar sensor, assuming production volume on an automotive scale. The focus in the effort is the type of sensor developed at TSC, and its cost could be significantly different for alternative techniques. However, these results do provide a useful baseline for examination of economic viability, and - in view of the similarity of the TSC design to other reported anticipatory sensors - the numbers determined here should have reasonable generality. It is, of course, quite possible that other techniques, or more extensive study of production aspects, could achieve even lower cost, or improved performance with little or no increase in price.

At the same time reliability - particularly of electronic circuits - has been examined carefully, for this, also, is a crucial factor in overall feasibility. The study has been in terms of the three separate functional elements of the sensor: antennas, microwave transmitter/receiver, and signal processor. The first and last items have required the more intensive examination, as microwave devices suitable to this application have received extensive commercial and military development and are more readily characterized.

5.2 ANTENNAS

Cost is only one constraint upon antenna selection. Size and shape convenient for automotive mounting, and near-invulnerability to the sometimes severe automotive environment are equally important to overall viability. Conventional horn antennas for the relevant frequencies, commonly used in laboratory systems (and in early versions of the TSC sensor), are relatively large and bulky, and - when fitted with a fully-protective "window" - can be relatively expensive. Furthermore, control of the beam characteristics (important to the tailoring of the sensitivity region) is rather difficult, and dents or bending can distort the pattern. It is not impossible that fabrication techniques can be developed which would make horn antennas acceptable, but there is clear motivation to consider other types.

Two alternative planar constructional concepts are relevant to this application, with numerous variations possible in each case. Both concepts involve utilization of an array of radiating elements (generally dipoles of some form) with the location of such elements, and the feed-line phasing between them selected so that the total radiation pattern, comprising the superposition of patterns for each dipole, achieves the desired shape. Antennas based upon this idea are limited by the convential constraints linking aperture size, wavelength, and beamwidth, but they can be fabricated in planar form, and the beam can readily be controlled by tailoring of the location and/or phasing of each radiating element. In the large phased array antennas developed for space and defense applications, the beam is often electronically aimed by adjustment of the phase of the energy fed to each dipole. However, for the automotive application at hand, this is unnecessary, and a fixed beam is satisfactory.

One method of realizing such an antenna is by forming an array of waveguide sections, as indicated in Figure 5-1. The antenna is fed by the bottom waveguide, and the slots act as radiating dipoles. The proper slot configuration can provide a net pattern with directivity approaching the theoretical maximum for the total area used. Many variations on this concept are possible, and permit emphasis of certain characteristics, such as narrow beamwidth, low-intensity sidelobes, or broad bandwidth.

An alternative concept utilizes printed circuit technology to form both feedlines and radiating elements on a standard PC board, indicated schematically in Figure 5-2. Again, many variations are possible, both in realization techniques and in underlying theory[15]. This method can provide an antenna limited in thinness only by the printed circuit board and the desired protective material on the front, and can even be shaped to follow the contours of the mounting surface. The microstrip feed-line is usually more lossy than is the case for waveguide feed, but this is a trivial effect for the antenna size and application considered here. Since operational factors showed no overwhelming advantages for either approach, manufacturing costs were explored for both cases. In addition, waveguide and PC antennas were purchased for use in test systems. The waveguide antennas, produced by the Rantec Division of Emerson Electric Co., have a particularly simple form, as shown in Figure 5-3; it turns out

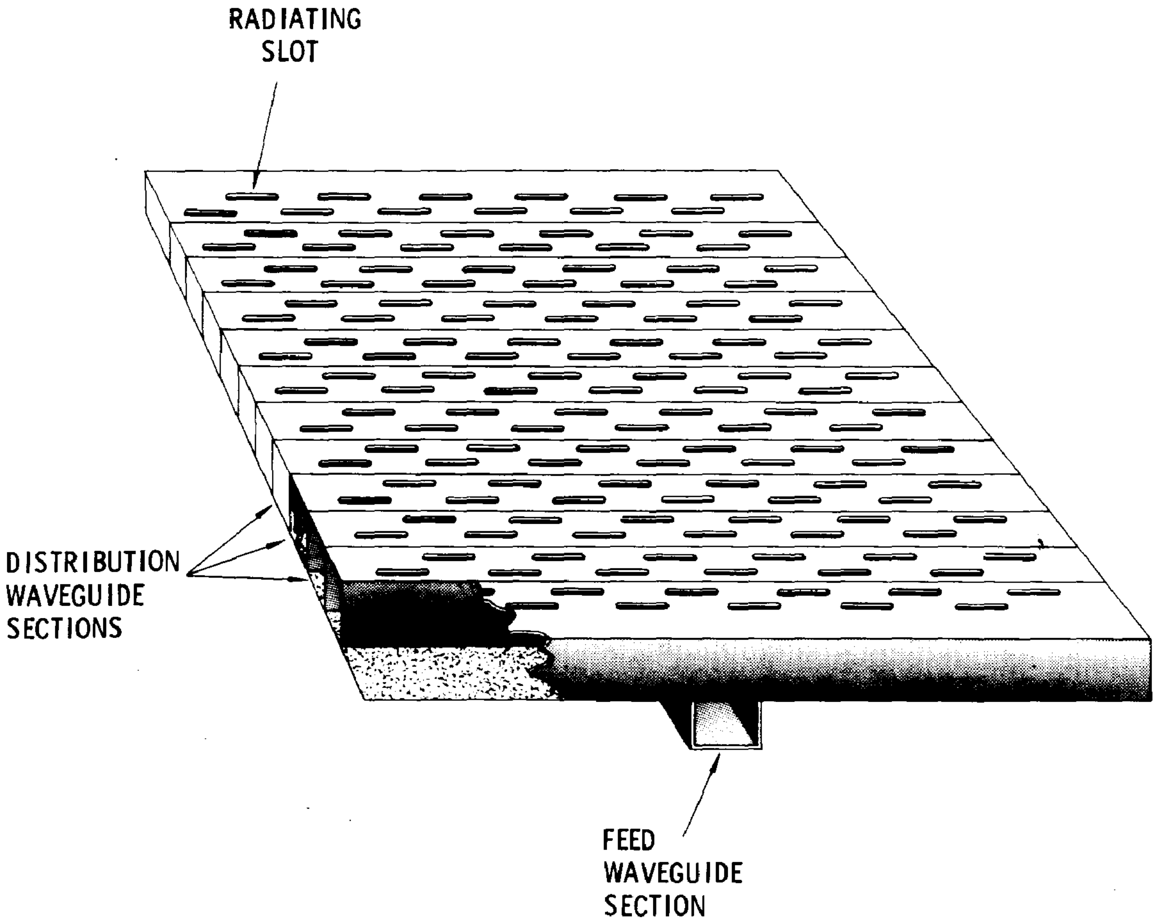


Figure 5-1 Basic Format Waveguide - Fed Slot-Array Antenna

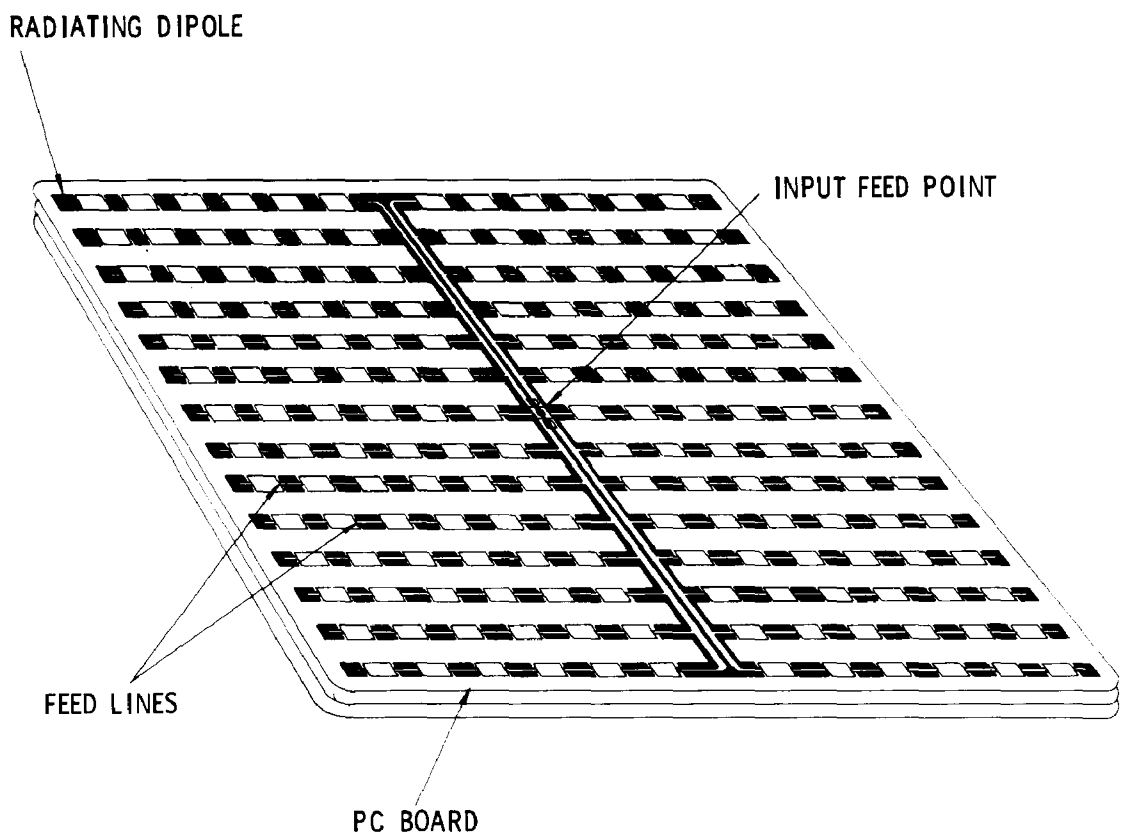


Figure 5-2 **Basic Form of Printed Circuit Antenna**

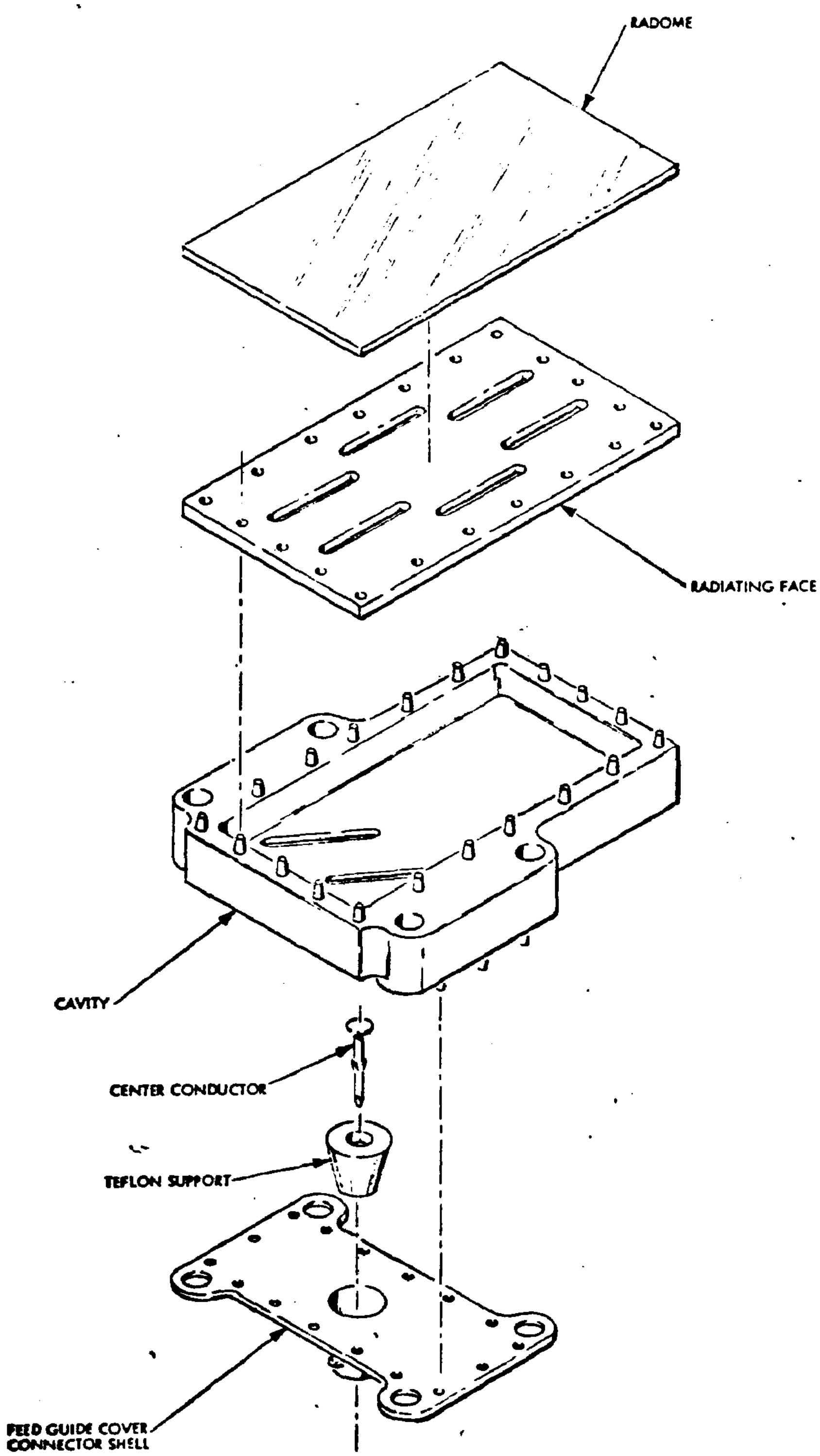


Figure 5-3 Flat-Plate Antenna Details

that the electromagnetic fields are such that the center wall is unnecessary. A complete antenna is shown in Figure 5-4. The analysis of production cost, carried out by Rantec, indicates a unit cost of \$.41 (total annual production of 10^6 units) and \$.29 (total production of 10^7); these figures do not include overhead, profit, etc.

A similar cost study for printed circuit techniques was carried out by the AIL Division of Cutler-Hammer. Their conclusion was that OEM prices (including overhead and profit) of \$3.25 and \$1.75 could be achieved for volumes of 10^6 units and 10^7 units, respectively. Figure 5-5 shows a printed circuit antenna purchased from Cheasapeake Microwave, Inc.; Figure 5-6 is an x-ray photo of the same antenna, showing the basic construction involved. (As stated above, a variety of antenna concepts are possible within both waveguide and printed circuit fabrication technologies, but cost should not be substantially different for different approaches.)

5.3 MICROWAVE SOURCE AND RECEIVER

As pointed out in an earlier section, solid state diodes - particularly gunn oscillators - appear well-suited to this application. The state of the art has improved steadily in recent years, and they are, in fact, in common service in police speed-measuring radars - a use which includes dependence upon automobile electrical power systems and a wide variety of operating conditions. No truly high-volume market has yet developed, but there is no reason to doubt that large-scale production would lead to the same economies here as for other solid-state

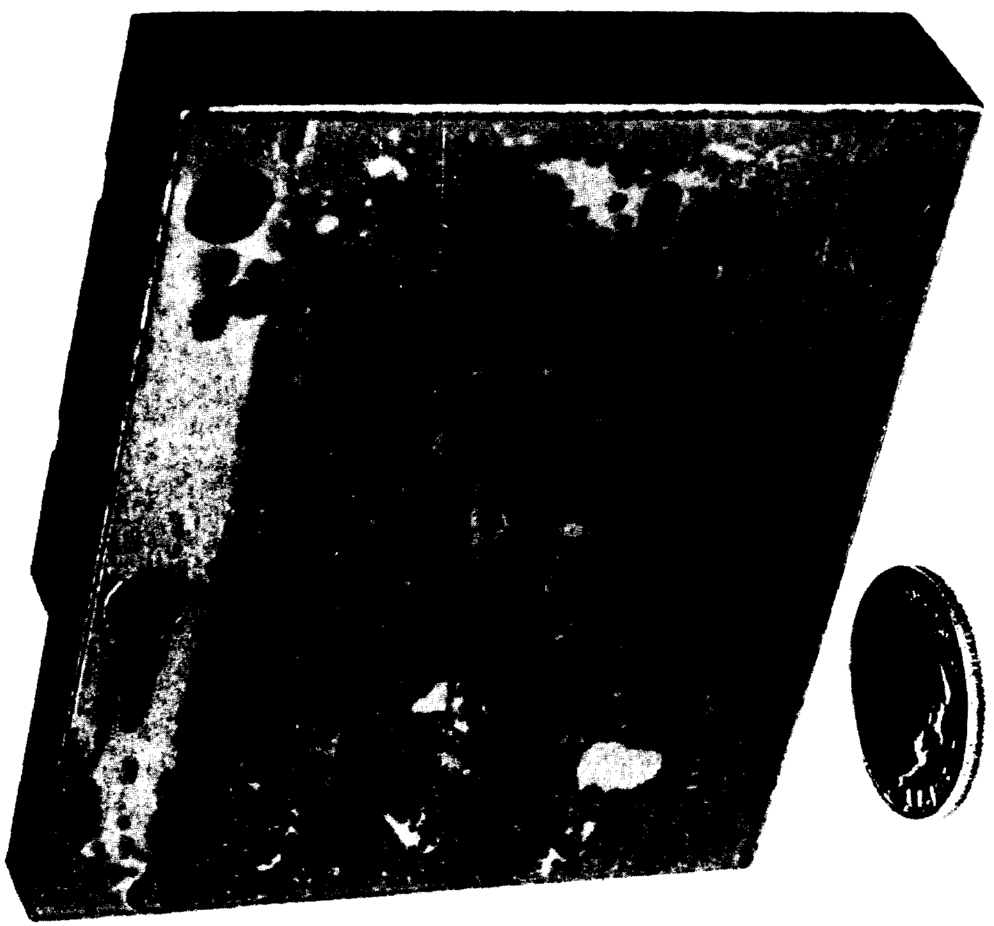


Figure 5-4 Slot-Array Planar Antenna

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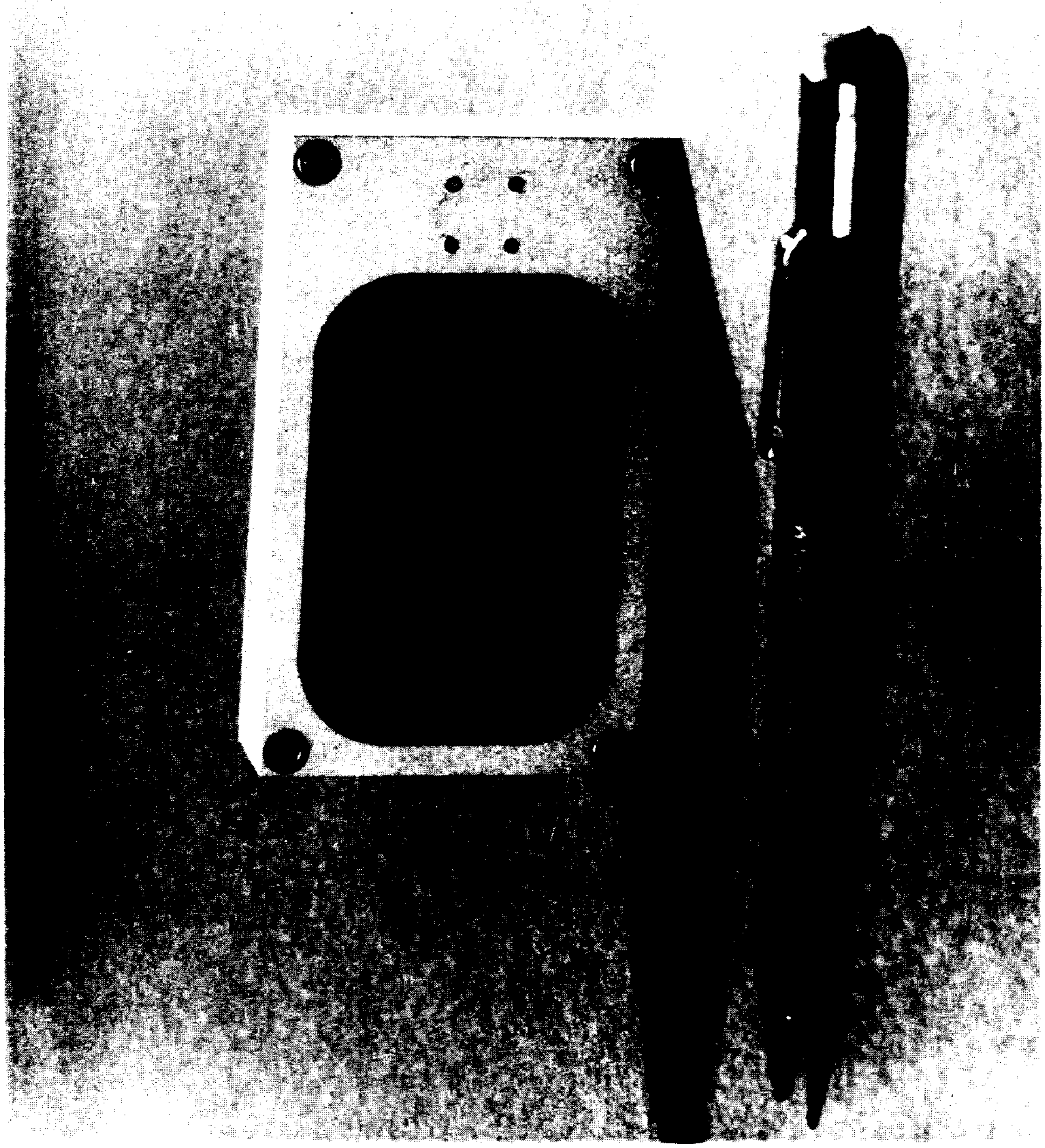

Figure 5-5 Printed Circuit Antenna

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Figure 5-6 X-Ray Photograph of Similar Printed Circuit Antenna

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components. (As long ago as 1970 one manufacturer advertized a unit price of \$5 for volume of 10^5.)

Basic device lifetime appears to be many tens of thousands of hours - very long when compared to the estimated 500 - 1000 hours of service typically experienced annually by personal motor vehicles. Problems associated with ageing, temperature, transients, etc. are well on the way to solution, and do not represent a serious problem within the time frame relevant to radar crash sensors. A significant portion of the present cost is associated with the device housing, and this could inexpensively be incorporated into the antenna of a production device.

Generally similar comments apply to the mixer diode which serves as the receiver front-end in the TSC sensor. However, mixer technology is considerably older and substantially less expensive devices are now available. It should be noted that this application, in which only large amplitude signals are of interest, is not a demanding one for the mixer.

In summary, it is reasonable to assume that given a production volume of 10^6 - 10^7 units annually, fabrication, design, and packaging optimization would lead to an OEM cost for the necessary microwave devices of the order of \$5 per vehicle.

5.4 SIGNAL PROCESSOR

The circuits which determine from the mixer diode output whether or not restraint system actuation is warranted are - insofar as electronic technology is concerned - the heart of the crash sensor. Aside from the problems of basic target discrimination - discussed elsewhere - proper operation depends upon complete assurance that triggering will occur whenever the selected criteria are met, and will never happen otherwise. For the signal processing section, which carries out this function, both cost and reliability are fundamental attributes, and have been explored in considerable detail.

This topic was studied under contract by the Defense, Space and Special Systems Group, Burroughs Corp., and is fully documented in a separate report. The results will be summarized here. The case considered is that of a hybrid sensor in which triggering occurs in the intermediate speed range only for impact switch confirmation, and on radar actuation only at higher speed. (Figure 5-7)

As part of this contract, Burroughs also furnished three breadboarded versions of the processor (Figure 5-8) as well as complete schematic drawings for fabricating the entire signal processor on two custom IC chips which could both be mounted into one hermetic package.

An optimum cost vs. reliability approach, that included circuit logic design, technology and techniques was established. This design was evaluated for quantitative reliability characteristics, including a detailed anaysis of failure modes and effects. The results and costs of using both voting and redundant logic signals were also investigated. The results demonstrate that in automotive volume (> 100,000 units/yr.), low cost (< $5.00) and high reliability (> .99999999) can be achieved concurrently with established intergrated circuit technology.

HYBRID, DIGITAL CRASH SENSOR OPERATION

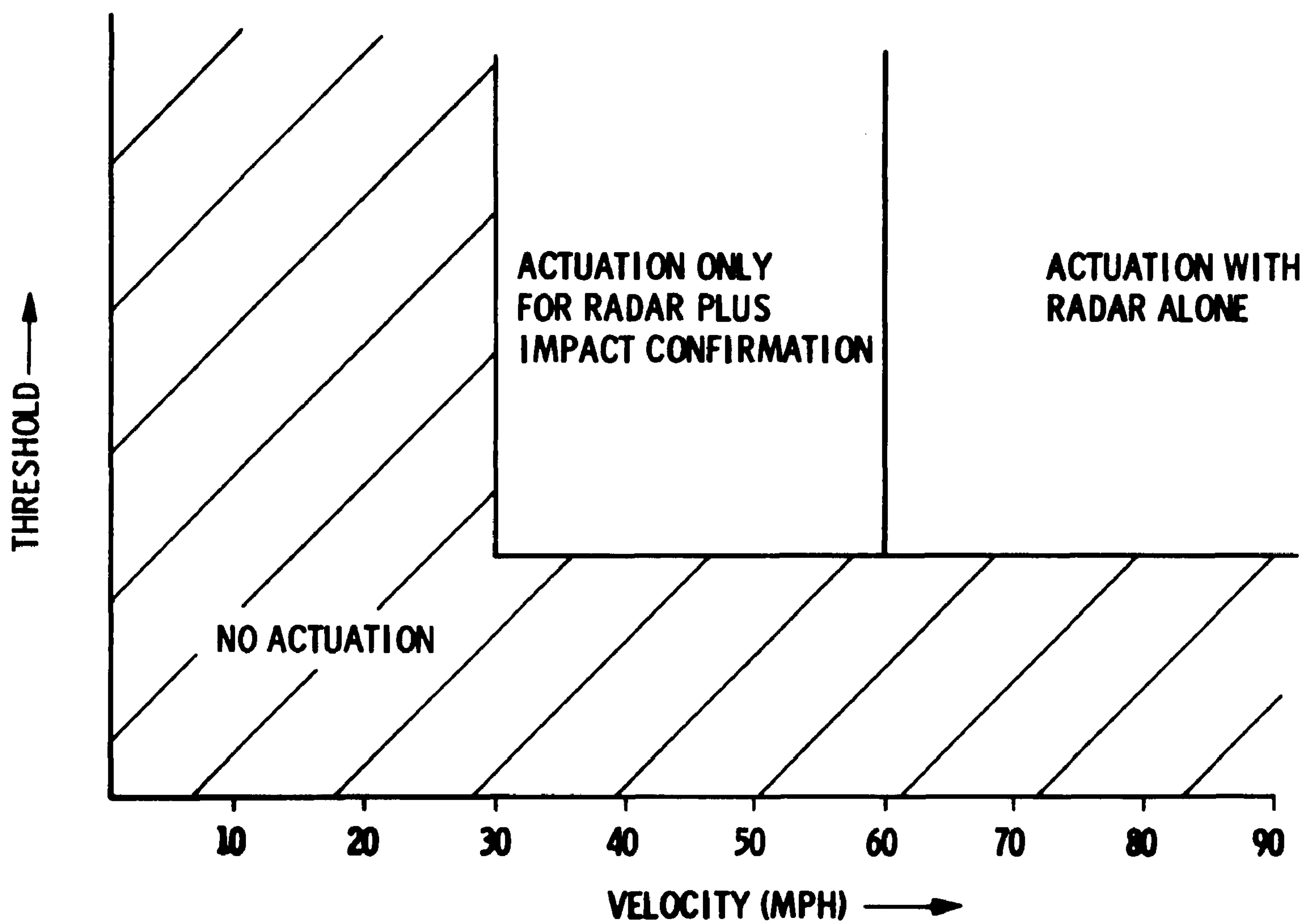

Figure 5-7 Radar Coast Sensor Actuation Criteria

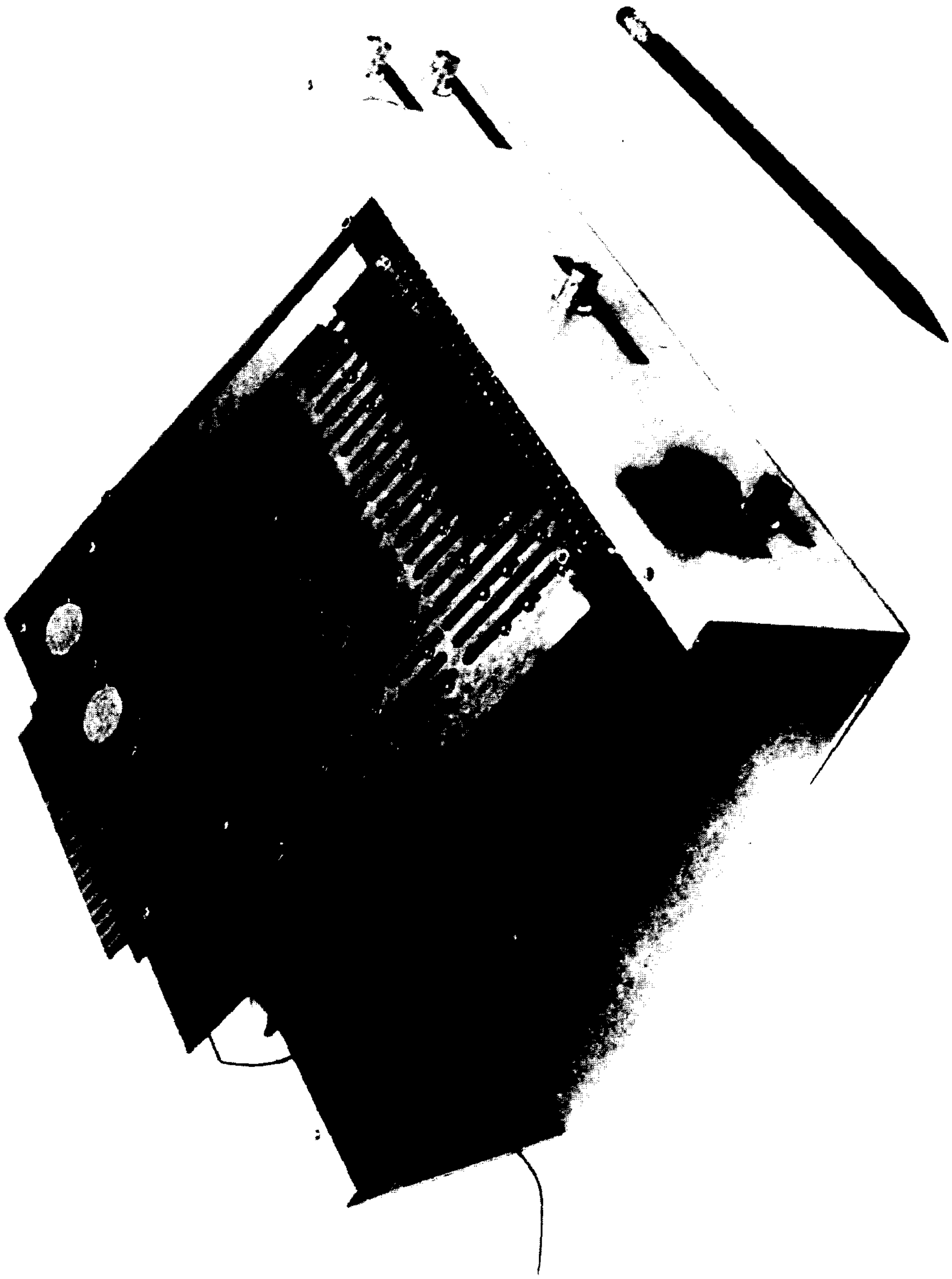

Figure 5-8 Prototype High-Reliability Signal Processor

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5.4.1 Design Approach

The signal processor performs three major functions -- Deployment Decision, Self-Test and Power Driving. For reasons given in a later section, the processor is divided into two regions. The first region is MOS-LSIC (Metal-Oxide Semiconductor Large-Scale Integrated Circuit) and performs the first two functions -- Deployment Decision and Self-Test. The second region is bipolar and performs the Power Driving function.

The Deployment Decision is the most complex function. The basic triggering criteria is shown in Figure 5-9. For circuit design purposes, an input signal level threshold of 20 mv was specified -- if this circuit were to go into actual use, the 20 mv threshold would probably remain fixed and the microwave mixer sensitivity could then be adjusted to generate a 20 mv output, for a specified input condition. Although a purely analog (i.e. filter/detector) approach to processing is feasible, the stated criteria are manifestly compatible with a digital system design. Burrough's approach was, therefore, a digital one. Figure 5-10 depicts the system organization. The radar signal is amplified and digitized in such a manner that one pulse is produced for each cycle which exceeds the action threshold -- 20 mv, peak to peak. Frequency bands are established by comparing the incoming pulse rate with that of a reference clock oscillator.

The reference clock establishes timing "windows", and if a certain number of pulses is registered before any of these timing "windows" expires -- 16 pulses during a 32 ms "window" for a

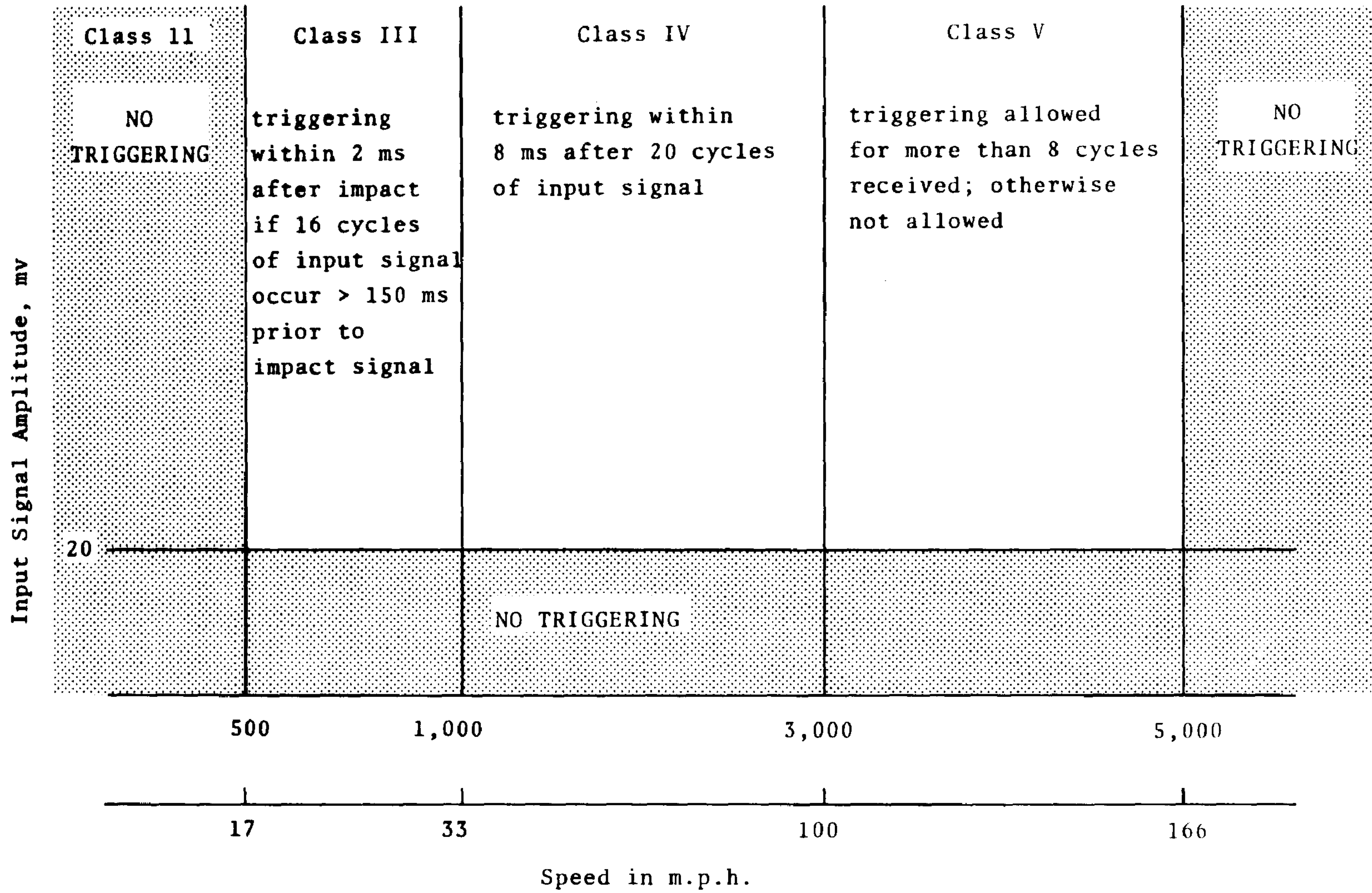


Figure 5-9 Actuation Criteria of Prototype

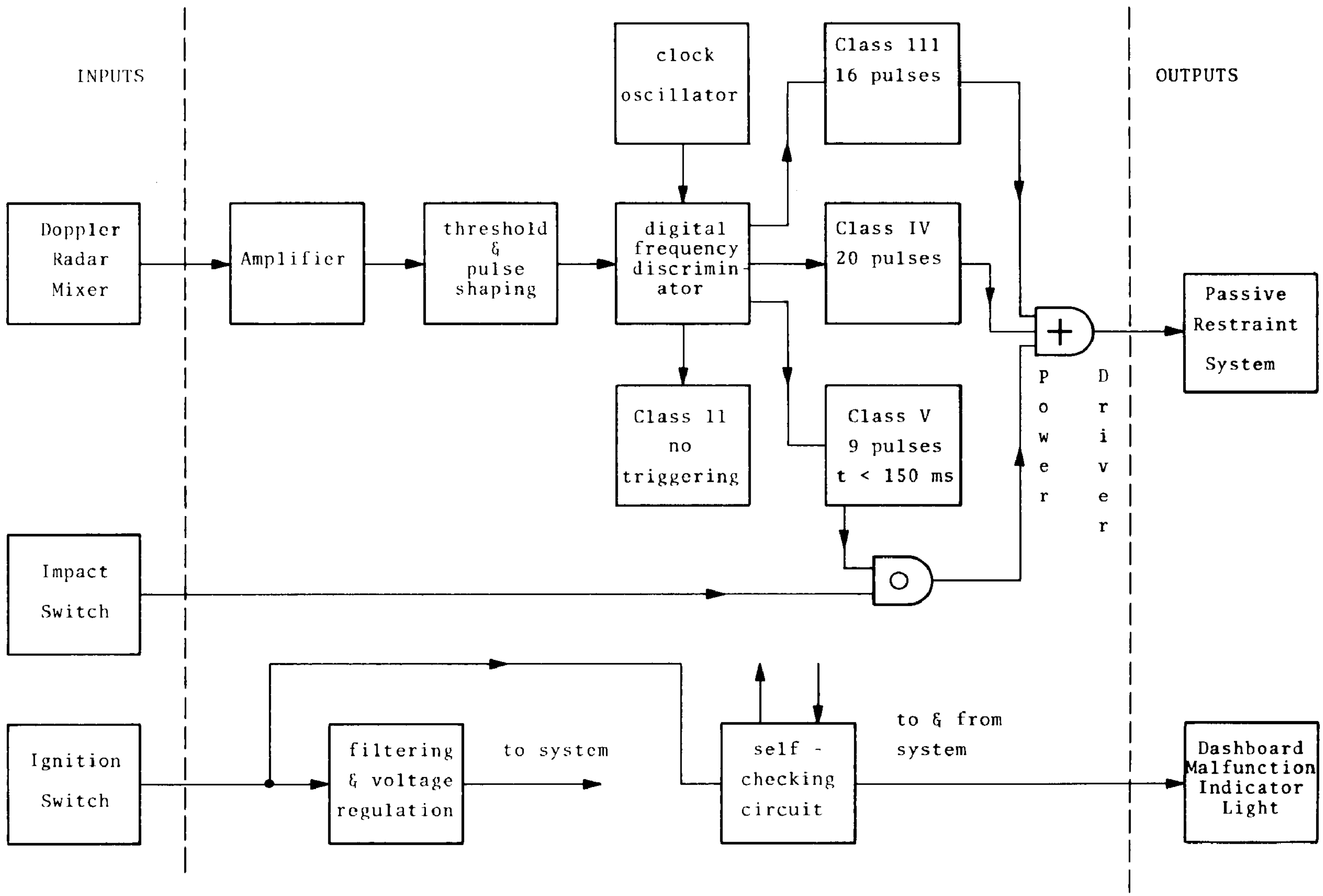


Figure 5-10 Function Organization of System

Class 111 trigger, 20 pulses during a 20.0 ms "window" for a Class 1V trigger, etc. -- the appropriate signal is sent ahead for further processing. After that digital filtering operation, the trigger signal, if present, is sent through a series of logic gates that determine whether or not activation is warranted. If activation is warranted, an activate signal is sent to the Power Driver chip.

The second major function of the Signal Processor is that of Self-Testing. Burroughs considered two different modes of Self-Test implimentation -- initiating a Self-Test program at engine start-up, and initiating the program at specified intervals during automobile operation; the engine start-up mode was selected. A special circuit in the processor senses when the ignition switch is first turned-on. The processor then initiates a Self-Test program during which the activation output is first inhibited, and then various standardized test signals are automatically applied to the input -- the impact switch is also simulated. During this operation 12 different tests are performed on the processor. If the Crash-Sensor Signal Processor fails to pass any of these tests, a warning light on the dashboard is illuminated and the activation output remains inhibited. If the unit passes all the tests, the inhibit signal is removed. Figure 5-11 shows a logic state flow diagram of the Self-Test diagram of the Self-circuitry.

The third function of the Crash-Sensor Signal Processor is that of Power Driving. The processor must be able to provide

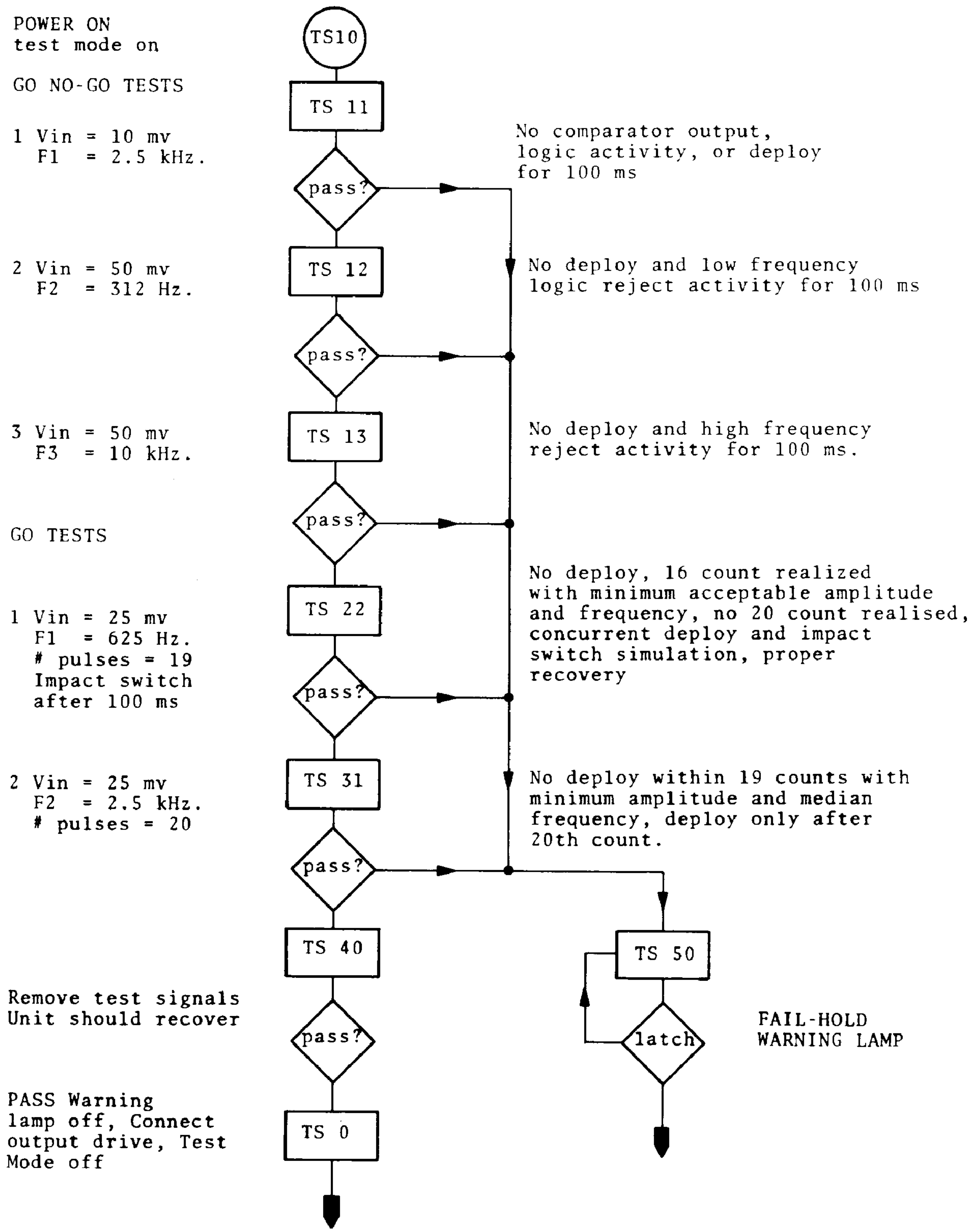


Figure 5-11 Logic-Flow Diagram of Self-Test Circuitry

direct drive for a restraint deploy solenoid or for an equivalent electromechanical device. This requirement may involve output pulse currents as high as ten amperes and inductive "kick" voltages as high as 100 volts. MOS devices are totally unsuited to these conditions, being limited in practice to peak currents on the order of ten milliamperes and breakdown voltages on the order of 30 volts. Consequently a circuit/technology partition was established where the low power logic deploy signal pulse is derived in the MOS processor chip which activates a high current Bipolar, small scale intergrated circuit chip. The Bipolar driver chip then serves as essentially a power amplifier for the MOS section. The basic form is indicated in Figure 5-12(a).

5.4.2 Reliability and Costs

The entire effort was directed toward high reliability at low cost. The processor was designed to keep the device count to a minimum, a special voltage regulator circuit was built into the processor, a temperature range of from -40 to +100°C was assumed, and an extensive pre-selection and "burn-in" process was recommended.

Also recommended is a doubly redundant circuit configuration as shown in Figure 5-12(b). Using this arrangement both MOS sections would have to agree before activation could take place. Also, both bipolar sections would have to agree that activation was warranted before activation could take place. If either MOS section failed to pass the Self-Test program, the warning light on the dashboard would become illuminated. Burroughs also investigated the feasibility of using voting and other types of

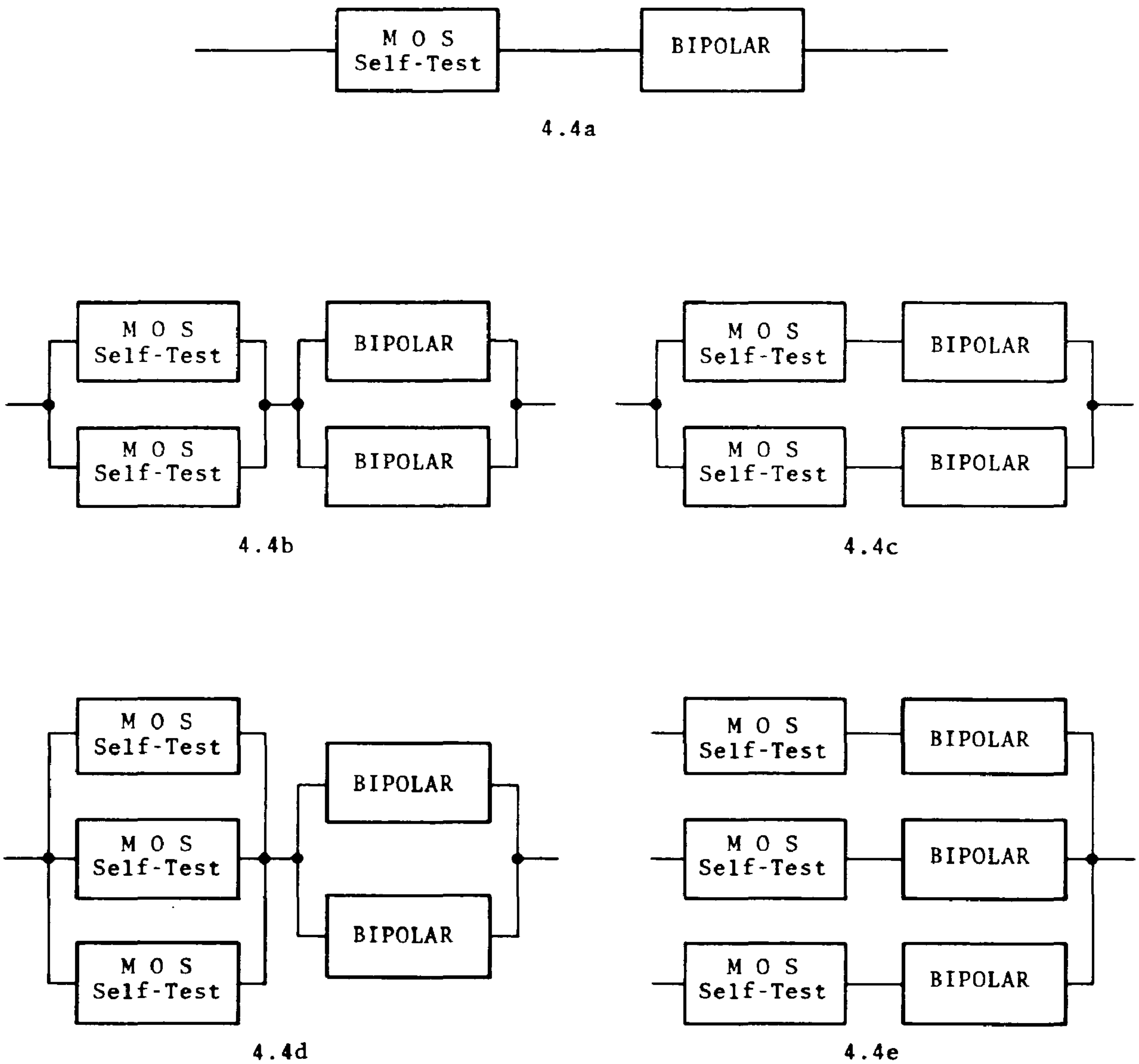


Figure 5-12 Alternative Redundancy Configurations

redundant circuitry, shown in Figures 5-12(c)-(e), but found that the configuration of Figure 5-12(b) was the most cost-effective.

Assuming a production volume of 100,000 units/yr., the basic doubly redundant self-testing, burned-in signal processor mounted in a hermetic package will cost approximately $4.90, $3.78, and $2.97 for production volumes of 10^5, 10^6, and 10^7, respectively. Burrough's predicted failure rate, for a circuit failure that would cause an unwarranted activation, is .00000013 failures/500 hrs. of operation; for a circuit failure that would cause the unit not to deploy when activation is warranted, the rate is .000234 failures/500 hrs. of operation. It should be stressed that these predictions are for the Signal Processor alone, not for the entire Crash-Sensor. Of course, 99% of these failures would be detected at engine start-up, during the Self-Test program. Judging from the figures presented above and assuming that there is 100 million automobiles in the U.S., each of which is driven for an average of 500 hours/yr., there would be less than 1 unwarranted activation per year and some 20,000 Self-Test failures per year, caused by the processor alone. Thus, it is clear that the signal processing circuitry imposes no unduly severe inherent constraints on either cost or reliability.

5.5 COST SUMMARY

There are numerous obstacles to precise estimation of the high-production-volume cost of complex devices for which final design concepts have not yet been determined. Development of a fully acceptable prototype would normally be accompanied and followed by an extensive effort directed at minimization of production costs. However, even at the present early stage of development, reasonable estimates can be generated. No new technology is involved, and the system concepts under consideration are based upon utilization of fully developed components and fabrication techniques. Thus, prices which have been mentioned earlier in this chapter may be assumed to be accurate at least to within a factor of two.

Based upon as assumption of annual volume of one million units, the studies here suggest realistic costs as follows:

Antennas (2 @ $3)	$6
Microwave Components	$5
Signal Processor	$4

An allowance of $3 appears reasonable for interface and interconnection components, leading to an estimated system cost of $18. It must be emphasized that this assumes the prior existence of a restraint system, electromechanical/impact sensor, and self-test dashboard indicator. Integrated packaging of the radar sensor elements and combination of the radar signal processor with the impact sensor circuitry can lead to further significant cost reduction. On the other hand, as suggested in Chapter 2, one must multiply the OEM price by a factor of four to eight to obtain a reasonable estimate of true societal cost. Thus, the actual total expense to the consumer associated with widespread installation of radar crash sensors may reasonably be expected to be in the range of $75 to $150 per vehicle.

6. ESTIMATION OF SYSTEM EFFECTIVENESS

6.1 INTRODUCTION

There are a number of means of estimating, with a reasonable degree of confidence, the effectiveness of a crash protection system. Cooke, for example, applies the performance requirements of the Occupant Crash Protection Standard to the current annual casualty toll and calculates the expected savings of deaths and injuries. This is done entirely in terms of the Standard, without regard for the protection system specific configuration, characteristics, or capabilities. The radar crash sensor system, however, is a real system, possessing certain characteristics, upon which can be based estimates of its effectiveness under the various crash conditions.

It is obviously very difficult to estimate the overall effectiveness to be expected in operational general usage for radar activation of passive restraints. The sensor has certain modes of operation, i.e., the probability of actuation is a function (intentionally or inherently) of vehicle impact speed, impact angle, and (very importantly) object struck. Similarly, the value of restraint actuation will depend upon the restraint system characteristics, which are a function of the above quantities plus overall vehicle crashworthiness, occupant position, etc. At present, virtually all of these relationships can only be estimated, very crudely in some cases. Further, to make use of such estimates, one must be able to describe the actual accident spectrum in terms of these characteristics, with estimates of the probability of each combination of parameters. Only if all of these data were known, would it be a simple matter to calculate the reduction in fatalities and serious injury associated with any sensor/restraint system combination. However, a sufficient information base is available to warrant an attempt at estimation of system effectiveness.

The method used at TSC is described here briefly and without formal mathematical derivation. For a more detailed description see Appendix B.

6.2 CRASH PARAMETERS

Accidents can be and are classified in a number of ways. For this analysis it is necessary to classify them according to characteristics, or parameters, which are independent of each other, and which also relate in some way to the characteristics of the crash protection system. Four crash parameters were chosen:

a. Target (object struck),
b. Velocity of crash vehicle,
c. Angle of impact,
d. Weight (or size) of crash vehicle.

Each crash parameter has a number of "values" associated with it such that every accident vehicle (and occupant death and occupant injury) of interest can be assigned a value for each parameter. For example, the weight parameter might have four possible values:

1) Cars below 2500 pounds,
2) Cars below 3500 pounds but above 2499 pounds,

3) Cars below 4500 pounds but above 3499 pounds,

4) Vehicles above 4499 pounds.

A parameter may have any number of values, but, to be practical, numbers less than ten will most likely suffice.

Every accident vehicle (or occupant death or occupant injury) then, can be placed into a "cell" of a four-dimensional array of cells. Each dimension of the array corresponds to a parameter, and the number of cells in the dimension corresponds to the number of values of that parameter.

6.3 STATISTICAL DATA

Existing statistical accident data, arranged to conform to the array description, can be utilized to perform the effectiveness estimation calculations. Care should be taken to exclude from the data deaths and injuries of non-occupants(pedestrians, occupants of other or stationary vehicles, etc.) since any passive restraint system would not affect the degree of casualty to non-occupants.

Data should not be considered for use unless the required parameter value information can be extracted for accident vehicles, occupant deaths, and occupant injuries. Additionally, injuries may be further broken down into various degrees of severity if desired.

Each cell of the array may contain any number of accidents, deaths, or injuries, as dictated by the statistical sample. If any one parameter (array dimension) is selected and the contents of all the cells is summed without regard for the values of the other parameters (summing of all cell contents orthogonal to the selected dimension), then a distribution of all the data with respect to the selected parameter only, independent of the others, is obtained for the sample. This summation can be repeated for the other three parameters.

Accident data will be obtained most conveniently in this summarized form, requiring only a few pages of data instead of the hundreds of pages that might be required to list contents of all the cells of the array. This simplification in handling of the data, however, implies a further assumption, that the data is product-form separable; i. e. the quantity in each cell can be reconstructed as being the product of four factors, a factor being known for each value of each parameter. The factors are found by means of a simple mathematical relationship to the summed distribution values described above. (See Appendix C)

This simplification can cause errors, particularly if the statistical sample is small. The analyst should endeavor to choose a set of statistical data sufficiently large, and distributed as nearly as possible among the cells proportionally to the national accident toll.

6.4 PROTECTION SYSTEM DATA

6.4.1 Deployment Probabilities (Sensing System)

For every value of every crash parameter there is some probability that the restraint system will deploy. This probability is a characteristic of the design of the sensing system being studied. For example, a system would not be very useful if its deployment probability were greater than zero for a velocity of zero, or if the target were a small aluminum foil "snowball" thrown in front of the car by vandals. On the other hand, a useful system should have a deployment probability approaching unity if, for example, the velocity is 60 mph, or if the target is a parked car. However, deployment probability might be 50% if the target is a tree, to allow for a wide variety of sizes, masses, and resistances offered by things called trees.

The deployment probability associated with each cell of the four-dimensional array is merely the product of the four probabilities assigned to the four parameter values associated with that cell. In the simple two-dimensional example cited above, the deployment probability in each cell can be calculated simply as in Table 6-1.

"Deployment" as discussed here shall mean that the restraint system is activated and in proper position at the proper instant for maximum reduction of occupant casualties. If, for a particular situation (parameter value), there is some possibility that the restraint system will be activated, but not in proper position at the proper instant for maximum reduction of occupant casualties, then that fact should be reflected in the value of the respective deployment probability by lowering its value.

6.4.2 <u>Reduction Factors (Restraint System)</u>

Assuming that the restraint system deploys (as defined in Section 6.4.1) in a particular accident situation, there will be a corresponding reduction in casualties, both deaths and injuries. This reduction will, of course, vary depending upon the values of the four parameters which apply to the particular accident

TABLE 6-1. TWO-PARAMETER EXAMPLE OF DEPLOYMENT PROBABILITIES

Dimension 1 Parameter: Velocity			Dimension 2 Parameter: Target			Array Cell	
Value	Description	Deployment Probability	Value	Description	Deployment Probability	Name	Deployment Probability
			1	"Snowball"	0	1,1	0
1	0 mph	0	2	Tree	0.5	1,2	0
			3	Car	1.0	1,3	0
			1	"Snowball"	0	2,1	0
2	60 mph	1.0	2	Tree	0.5	2,2	0.5
			3	Car	1.0	2,3	1.0

situation. The ratio of casualties (deaths or injuries) prevented by deployed restraints to casualties that would occur without restraints is called the reduction factor. A completely effective restraint system would, then, have a reduction factor of unity. Reduction factors for deaths and injuries may be estimated for each value of each parameter, independent of the other parameters, in the same way that deployment probabilities were assigned. However, they will be a function primarily of the restraint system characteristics rather than the sensing system characteristics.

The reduction factor associated with each cell of the four-dimensional array is merely the product of the four reduction factors assigned to the four parameter values associated with that cell, just as in the case of deployment probabilities.

6.5 EFFECTIVENESS ANALYSIS

The two quantities called deployment probability and reduction factor are used as operators to operate upon the statistical accident data to predict estimated occupant protective system effectiveness. The two quantities are themselves estimates of predicted sensor system and restraint system performance. The final result of the effectiveness analysis, then, is no more accurate than the estimates of the two quantities and will in all probability be slightly less accurate because of the additional error due to assuming that the statistical data is product-form separable.

All of the data discussed to here is input data, and a review of it, and the form it is in, is in order. Each of the items of input data in Figure 6-1 consists of four one-dimensional arrays (vector arrays), each array having a length equal to the number of possible values of its respective crash parameter, normally less than about ten. That amounts to less than about 40 total values which need to be stored for each item. Note that the statistical data required are not the quantities themselves but are the product-form factors simply derived from them. Each of the six items implies the existence of a four-dimensional array of cells but it will not be necessary to construct those arrays. The cell contents will need to be examined one-by-one so that the output data, consisting of two items, each in the form of four one-dimensional arrays of values, can be generated. Obviously the computational task is large, even for small numbers of parameter values. For example, an analysis using five values for each of the four crash parameters requires 1250 cell calculations (625 for fatalities and 625 for injuries) plus the four-way summing of results. The task is best handled by a digital computer.

The calculation at each cell location consists of evaluating a simple expression for the output item as a function of the input items, each of which are products of four known factors. The results are added to the proper accumulating four-way sums before going on to the next cell calculation so that no cell contents need be stored for later retrieval.

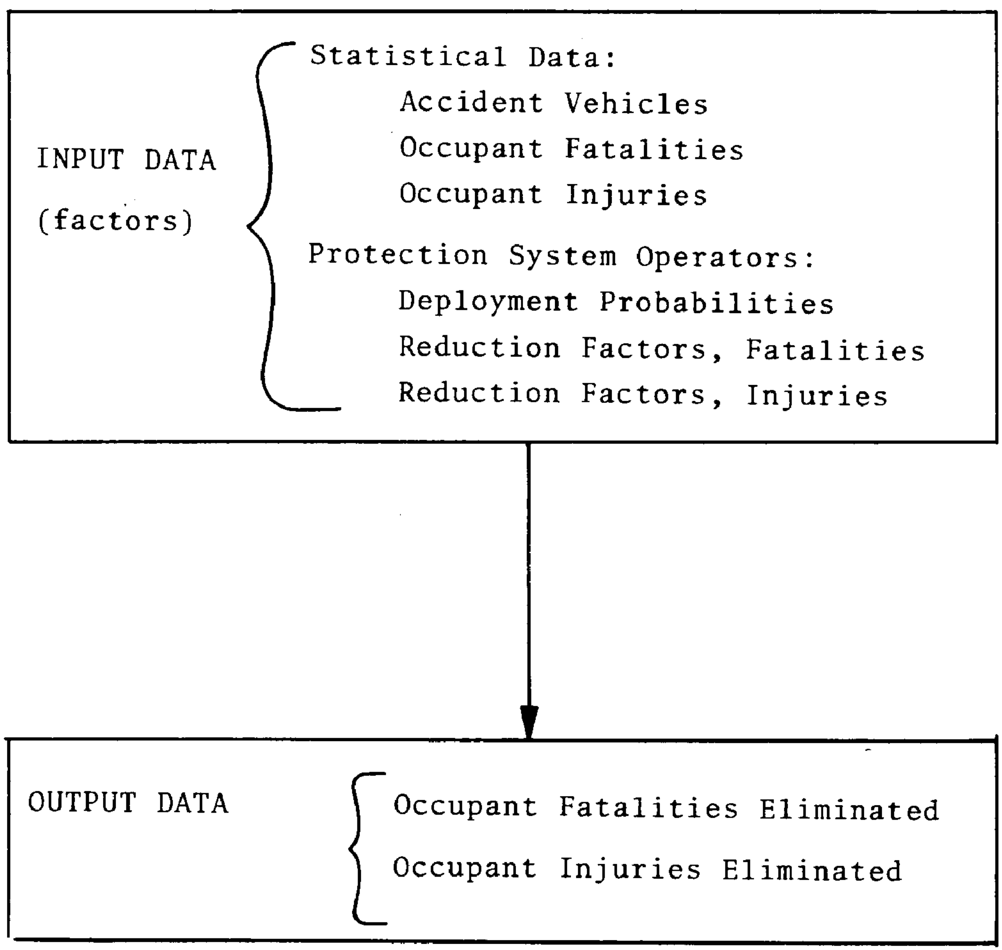


Figure 6-1 Input and Output Data in Four Vector Arrays

6.6 INPUT DATA

6.6.1 Accident Data

6.6.1.1 ACIR Data -

Summary tables of Cornell Automotive Crash Injury Research (ACIR) data were made available to TSC by NHTSA. The ACIR data bank then used was made up of crash data for vehicles of model years 1926 thru 1969, and included data on 81,633 vehicles and 169,959 occupants. Model years prior to 1956 were eliminated from the record for purposes of this study, so that the total sample size examined was 60,775 vehicles and 125,418 occupants. However, the ACIR data was gathered for all types of automotive accidents, regardless of degree of casualty to occupants. For this study, the following accident types were eliminated:

a. Accidents in which there was no occupant fatality or serious injury. (Serious injury is one which disables or hospitalizes beyond day of accident.)

b. Accident vehicles which were struck from the rear.

c. Rollover accidents.

After this further elimination, the sample size became 5425 vehicles, 4962 serious injuries, and 2018 fatalities, a much smaller sample than hoped for.

The ACIR data was classified into eleven targets, nine velocities, seven impact angles, and four vehicle weights. Probably because the sample size was so small and because the data gathered mostly from rural accidents, the distribution of accident/vehicles, fatalities and injuries among the parameter values may not be ideally representative of the national experience. Nevertheless, the ACIR data was found to be the best readily available and proved to be useful for a number of effective analyses.

6.6.1.2 National Data

Some attempt at using the raw national data was made, but proved to be futile. Not enough information is available in one source to provide enough values of the parameters, particularly targets and impact angles, to allow a meaningful analysis. Some of the runs using the ACIR data, however, were scaled to national levels by simple ratio multipliers to give an approximation of the national experience. The 1969 record was used, consisting of 2,470,700 accident vehicles, 43,740 occupant fatalities, and 1,787,000 occupant serious injuries.

6.6.1.3 HSRI Data

The large computerized accident data files maintained by the Highway Safety Research Institute of the University of Michigan, at first inspection seem like a good source of data for this effectiveness analysis. Further examination, however, showed that only a small number of files recorded any kind of velocity information and those that did were so devoid of target or impact angle information that it seemed unlikely that a worthwhile set of data could be extracted. In some files the required information was present, but organized in such a way that made it extremely difficult to reorganize into a form compatible with this analysis. Velocity data is essential to this analysis, but because it is seldom known with certainty in an accident situation (usually it is the reporting officer's estimate based on observed damages), the trend today is to omit speed information from the accident record.

6.6.2 Protection System Data

The deployment probabilities and reduction factors used with the ACIR data are themselves estimates of system (sensing system and restraint system, respectively) performance. Since there is a degree of uncertainty in their values, it was felt wise to use a range of values in many cases. The graphical representations that follow are merely approximate, not exact, distributions of the values used. For exact values used, see Appendix D, where the input values are shown with the output data.

6.6.2.1 Sensing System (Deployment Probabilities) - Estimated deployment probabilities are shown graphically for targets, velocities, and impact angles in Figures 6-2 through 6-4. Deployment probability was considered independent of vehicle weight and is a constant 100% for that parameter. These estimates are based upon the measurements described in Chapter 4, but must be considered approximations only.

6.6.2.2 Restraint System (Reduction Factors) - Estimated reduction factors for both fatalities and serious injuries are shown graphically for velocities, impact angles, and vehicle weights in Figures 6-5 through 6-8. Reduction factor was considered independent of target and is a constant 100% for that parameter.

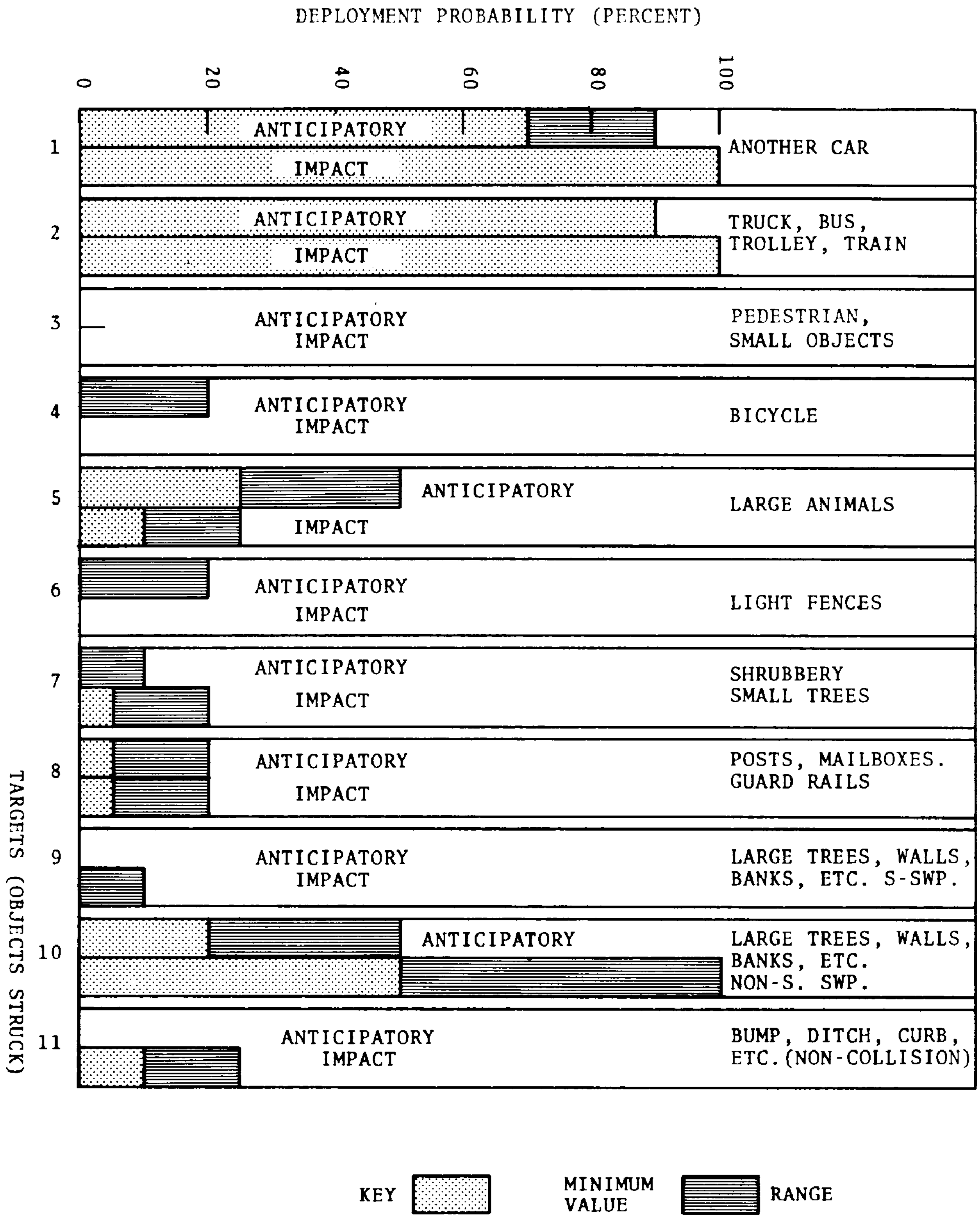


Figure 6-2 Deployment Probability Used for Target Parameters (ACIR)

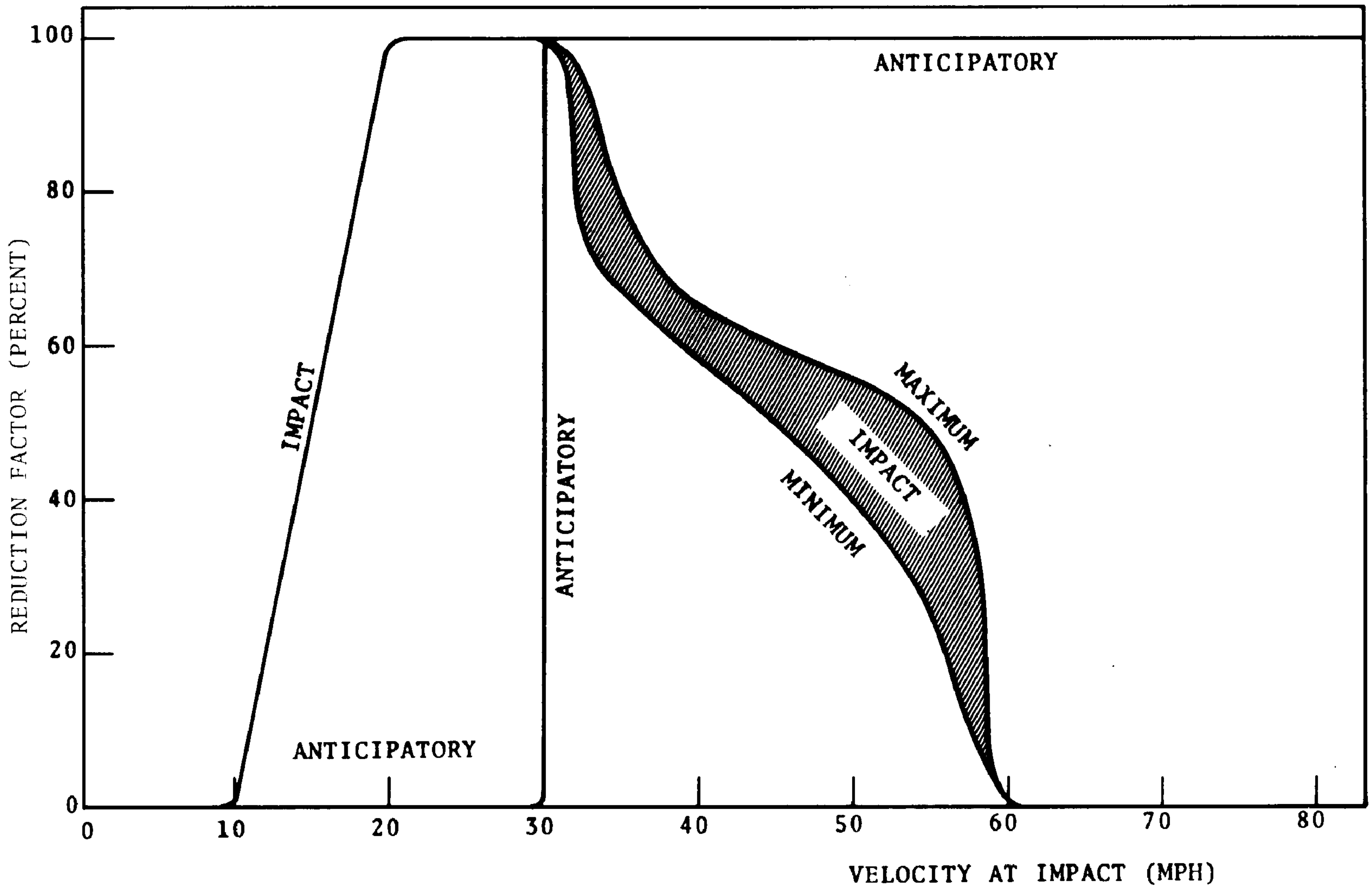


Figure 6-3 Deployment Probability for Velocity Parameter (ACIR)

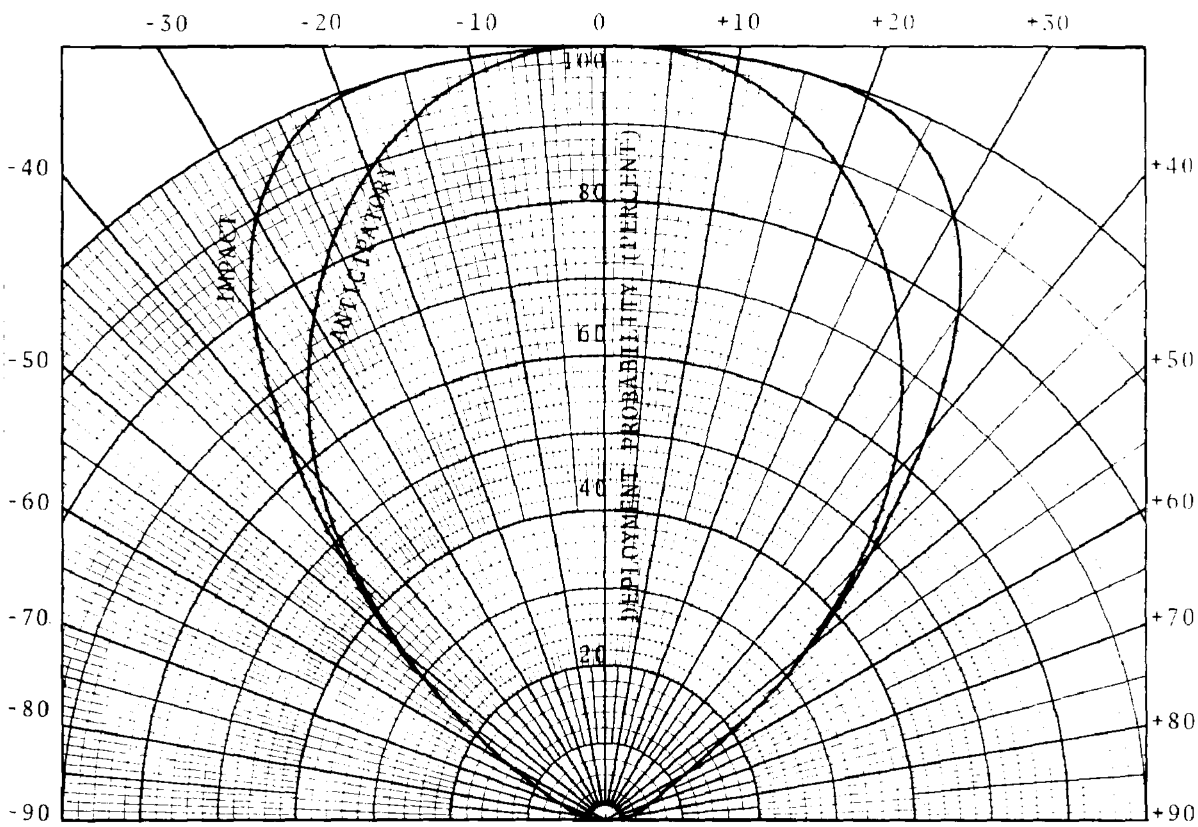


Figure 6-4 Deployment Probability for Impact Angle Parameter (ACIR)

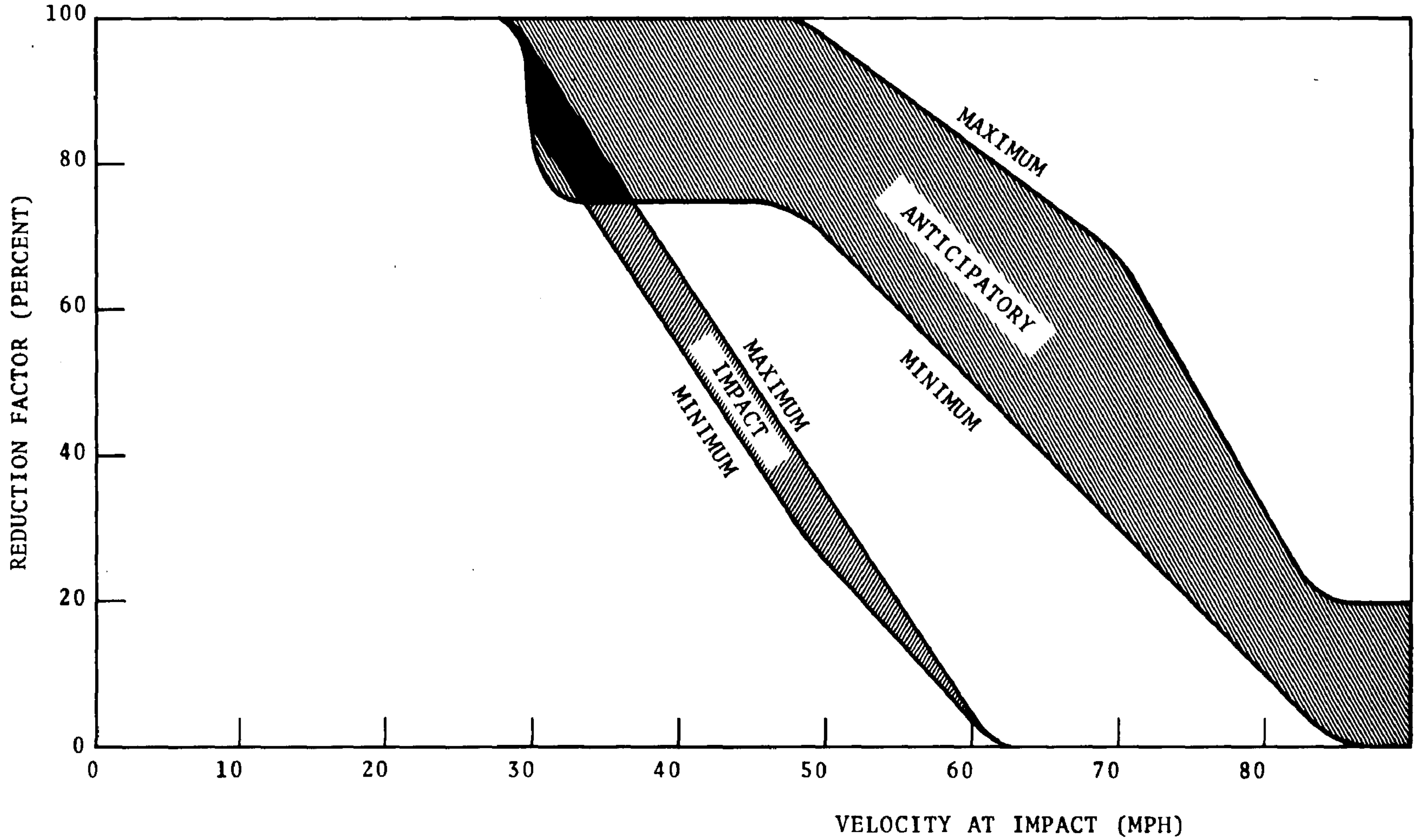
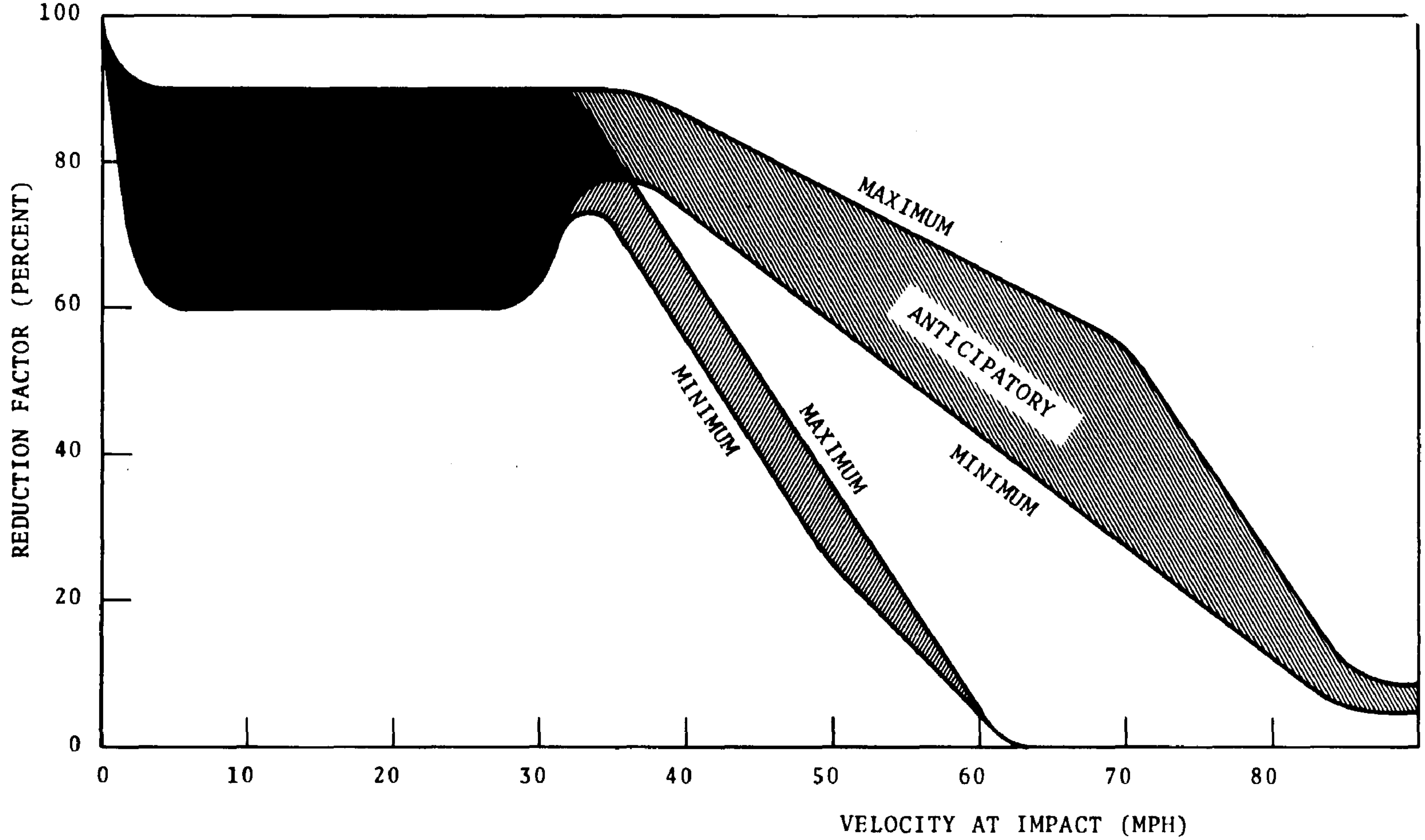


Figure 6-5 Fatality Reduction Factors for Velocity Parameter (ACIR)



SERIOUS INJURY REDUCTION FACTORS FOR VELOCITY PARAMETER (ACIR)

Figure 6-6 Serious - Injury Reduction Factors for Velocity Parameter (ACIR)

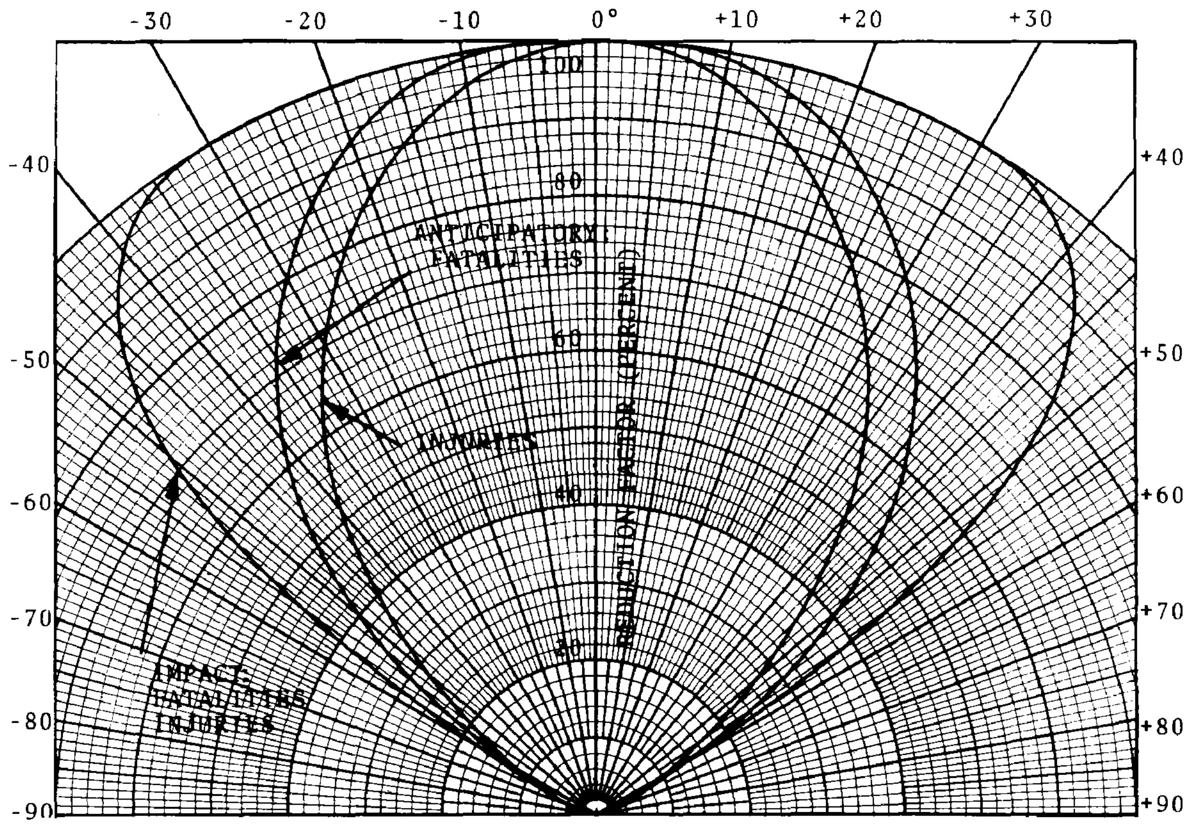


Figure 6-7 Reduction Factors for Impact Angle Parameter (ACIR)

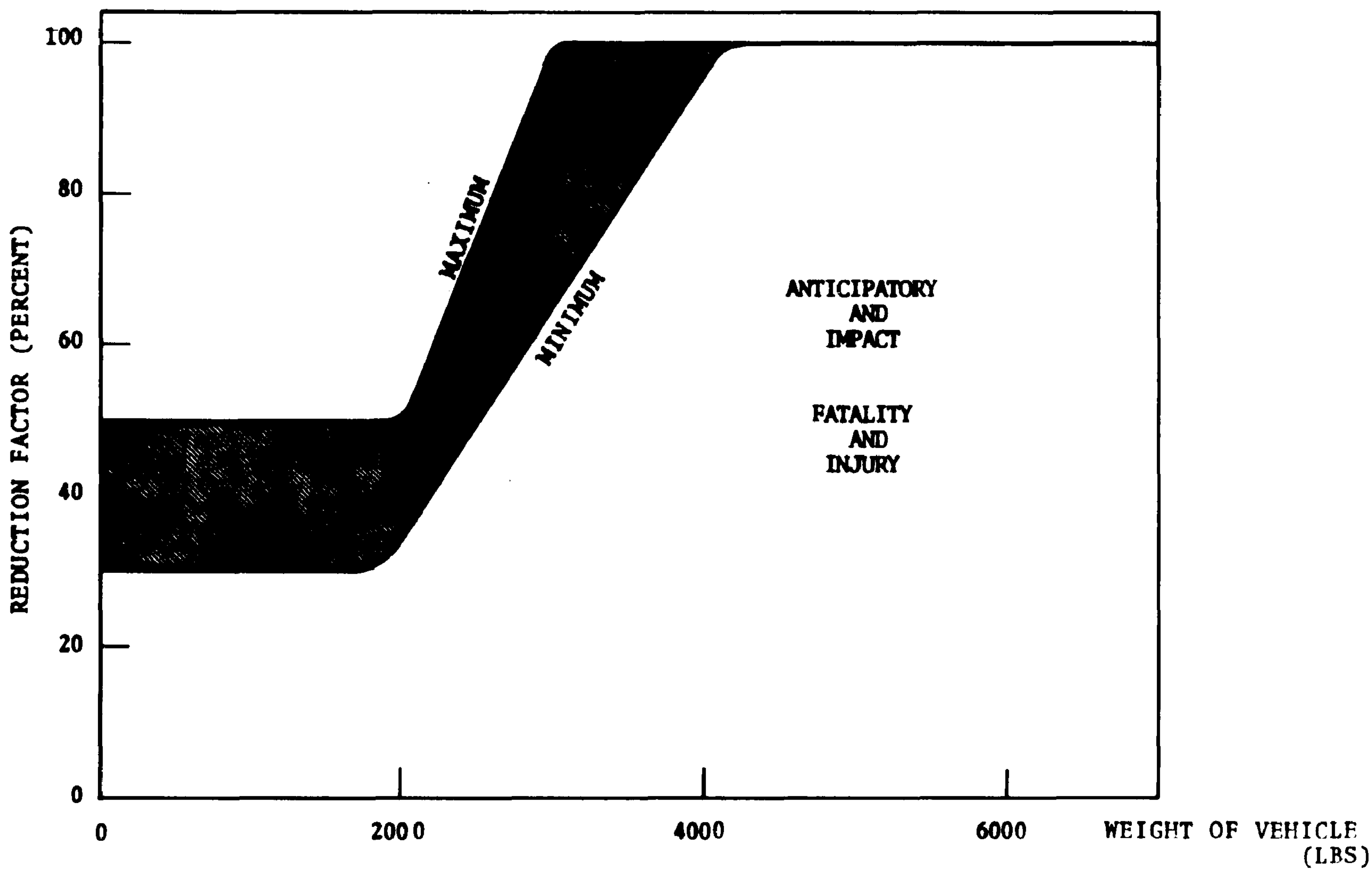


Figure 6-8 Reduction Factors for Vehicle Weight Parameter (ACIR)

6.7 RESULTS

Two sets of values of operators (deployment probabilities and reduction factors) were used with the ACIR statistical data in order to provide a range (minimum and maximum of estimated results. The results, in the form of computer program output, are shown in Appendix D as Run 23 (maximum operator values) and Run 24 (minimum operator values).

The protection system described by the operators is a hybrid sensing system and an air-bag restraint system. The hybrid sensing system consists of two subsystems, one a radar anticipatory system and the other a bumper-mounted impact system. Results for the two sensing systems are computed separately (pages 1-4 and pages 5-8, respectively, in Appendix D and then combined pages 9-12).

Readers are reminded that the results are only estimates, and are subject to a number of errors described throughout this chapter, most notably:

a. The accident data is assumed to be product-form separable, implying mathematical independence of the our crash parameters.

b. The ACIR data is a small sample (only 5425 accident vehicles).

c. The ACIR data, being primarily rural in nature, may not have the same proportional distribution of accidents, deaths, and injuries with respect to the crash parameter values, as does the national accident record.

d. The protection system operators are themselves performance estimates. Both deployment probability and reduction factor can only be very approximate at this time.

The tables of computer results, summarized in Table 6-2, show the possible savings for the hybrid protection system, based on national annual totals of 43,740 occupant fatalities and 1,787,000 occupant serious injuries which occur in the absence of any passive restraint system.

TABLE 6-2. SUMMARY OF RESULTS

		Anticipatory Sensing Only		Impact Sensing Only		Hybrid System	
		No.	%	No.	%	No.	%
Fatalities Saved	Max	14,450	33	5,950	14	20,400	47
	Min	5,900	13	3,300	8	9.200	21
Serious Injuries Saved	Max	513,700	29	407,200	23	920,900	52
	Min	235,000	13	195,200	11	430,200	24

7. PROBLEMS OF THE ELECTROMAGNETIC ENVIRONMENT

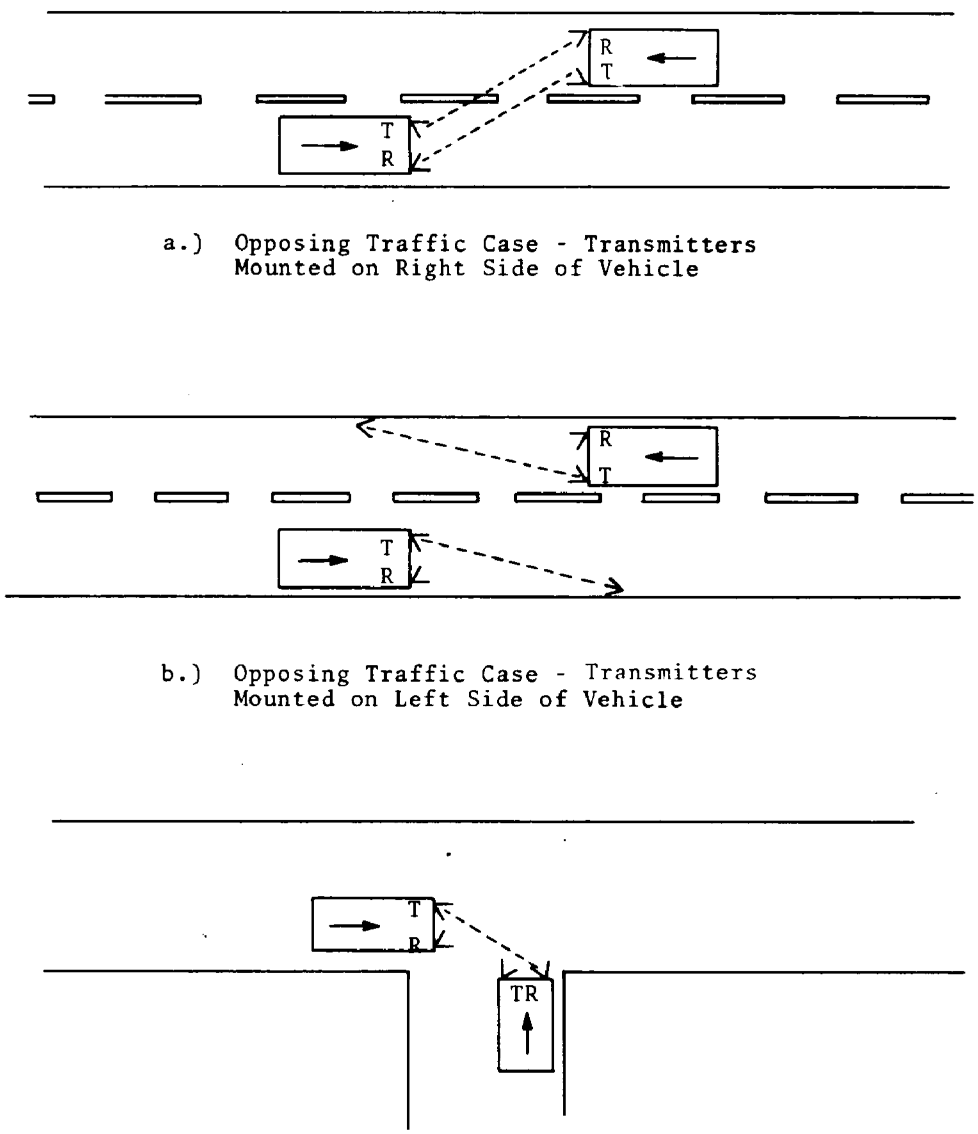
There are two aspects to problems of electromagnetic environment that must be examined in relation to the use of microwave crash sensors. One aspect is the potential problem of intervehicle interference in an environment in which every vehicle on the road equipped with a microwave crash sensor can expect continually to encounter other vehicles similarly equipped. All vehicles would emit essentially the same type of signal, in approximately the same portion of the spectrum. Each automobile's system would then have to separate unwanted signals from other automobiles from the doppler-shifted echos of its own transmitted signal. The other aspect is the possible great increase in exposure to microwave radiation for the public at large and especially for automobile service personnel. These two aspects will be considered in this chapter.

7.1 INTERVEHICLE INTERFERENCE

As suggested in Chapter 2, one means of avoiding intolerable levels of intervehicle interference is by "coding" the transmitted signals of microwave crash sensors. Recall that the microwave crash sensor system discussed in this report operates as follows: A cw microwave signal is transmitted. When the signal is reflected by a target immediately in front of the automobile, it is received by the crash sensor as a doppler-shifted signal having a frequency equal to the transmitted microwave frequency plus the doppler frequency f_d, which has the value $f_d = 30\ v_{mph}$ Hertz for a microwave operating frequency of 10 GHz. Thus, for relative velocities of target and automobile between 15 mph and 170 mph, the doppler frequency will lie between 450 and 5000 Hertz. When a sufficiently large doppler-shifted microwave echo is received and lies within 5 kHz of the transmitted signal, a doppler signal is produced, the doppler beats are counted to test for relative target speed, and provided that the amplitude and speed criteria are met, the system actuates. In the particular system under consideration the actuation criterion is that 16 doppler cycles with amplitude above threshold be recorded by a counter before the counter is reset, with reset occurring 36 msec after the initial cycle.

Consider the case of an automobile with a microwave crash sensor passing another automobile similarly equipped, traveling in the opposite direction. The second automobile's transmitting antenna may be aimed momentarily at the first vehicle's receiving antenna. Should it happen that the second automobile's transmitted frequency lies within 5 kHz of that of the first automobile and the vehicles are sufficiently close for the signal received by the first automobile to be sizeable, the first automobile will then perceive a signal that to all intents and purposes appears to be a large doppler-shifted echo of its own transmitted signal, and its passive restraints will be actuated.

To understand the magnitude of this potential problem, assume that the FCC sets aside a 100 MHz-wide band in the X-band range for microwave crash sensors, and the carrier frequencies of crash sensor systems in use are randomly and uniformly distributed throughout this range. Then the probability of two automobiles that encounter each other having carrier frequencies within 5 kHz of each other is $(2 \times 5000)/10^8 = 10^{-4}$. The threshold sensitivity of a practical microwave crash sensor may be as much as 10 dB below the signal reflected from a large metal surface at distance from automobile of 1 meter (round-trip distance 2 meters). Since microwave power density drops off as $1/R^2$ with distance from source, one automobile's signal transmitted directly into another automobile's receiving antenna from a distance of approximately 6 meters could then be expected to trigger the second automobile's passive restraint system on the average of once every 10^4 such encounters. Interactions of this type should, in fact, be relatively rare, due to the antenna configurations. Note in Figure 7-1a that the normal approach to opposing traffic places the transmitting and receiving antenna beams at approximately a right angle with respect to each other, and neither car will "see" the other due to the directional nature of the antenna patterns; this effect is greatly enhanced if the transmitting antennas are on the left side of the vehicle as in Figure 7-1b. The situation that poses a problem is illustrated in Figure 7-1c, in which cars are perpendicular as at traffic intersections. Although this situation can be made less difficult through deactivation of the system for any vehicle at rest, it remains possible that interference-induced inadvertent actuations still could occur too often for public acceptability, for which the tolerable level is of the order of one occurrence in ten to one hundred driving years. Thus, it is necessary that means be developed to enable one microwave crash sensor to clearly identify its own reflected signal and to ignore the signals that is receives from other crash sensors.



a.) Opposing Traffic Case - Transmitters Mounted on Right Side of Vehicle

b.) Opposing Traffic Case - Transmitters Mounted on Left Side of Vehicle

c.) Perpendicular Traffic Case

Figure 7-1 Interference Potential for Various Vehicle-Vehicle Configurations

7.1.1 Coding Techniques

In order to accomplish this end, a number of coding and modulation schemes have been considered. An immediately-apparent constraint is that any coding scheme, in order to be acceptable, would have to be implemented with very simple circuitry, and would have to rely on techniques compatible with the remainder of the microwave crash sensor's doppler signal processing system. The basic strategy that has been followed is frequency modulation of the transmitted microwave signal, so that a microwave crash sensor, using its own transmitted signal as the local-oscillator or reference signal, could recognize its own echos and ignore the signals from other sources.

The process of homodyne detection is inherently a correlation process; therefore, frequency modulation coding can be very simply implemented when homodyne detection is used. In the microwave crash sensor system, one simply must modulate in a manner that causes the relative phase of transmitted and received echo signals to be a very strong function of target distance and a weaker instantaneous function of time due to the modulation. The purpose of the modulation is then to insure that even if two potentially interfering microwave crash sensors have frequencies near each other on the average, the relative phases of the two signals will be so scrambled and will vary so rapidly that the beat frequency signals can readily be filtered out by a low-pass filter in the doppler signal processing circuit.

The potential interference is proportional to the bandwidth of this filter. Five KHz was chosen as the system doppler bandwidth.

This frequency corresponds to the doppler signal produced (in a 10 GHz system) in a head-on crash between vehicles travelling 85 mph--above a reasonable maximum effective velocity for any passive restraint system.

7.1.2 Frequency Sweep-Rate Coding

One of the first coding schemes considered, and due to its simplicity - the first one experimentally studied, was that of frequency sweep-rate coding. The basic idea of this scheme is as follows: Assume that every microwave crash sensor operates so that its transmitted carrier frequency sweeps over the entire assigned band according to the sawtooth function pictured in Figure 7-2. It is seen that periodically the carrier frequency crosses the carrier frequency of the potential interfering signal. Assume that these two signals have instantaneous microwave frequencies $f_a(t)$ and $f_b(t)$ that are both linear functions of time in the vicinity of crossing. Let f' be defined by $f' = d(f_a-f_b)/dt$. Then the beat frequency signal out of the crystal mixer due to the simultaneous presence of both of these signals at the input will vary as $\cos(2\pi f't^2)$, where the signals are assumed to cross in frequency at time t=0. This beat frequency will have a waveform as shown in Figure 7-3a. The specific waveform shown there is the audio-frequency output signal from a crystal mixer for which the input microwave signals were a 10.5 GHz fixed-frequency signal, and a microwave signal that was sawtooth-swept between limits above and below 10.5 GHz at a rate of 25 MHz/sec. The fall-off of signal strength before and after the crossing point is due to the frequency-response characteristics of the mixer output circuit.

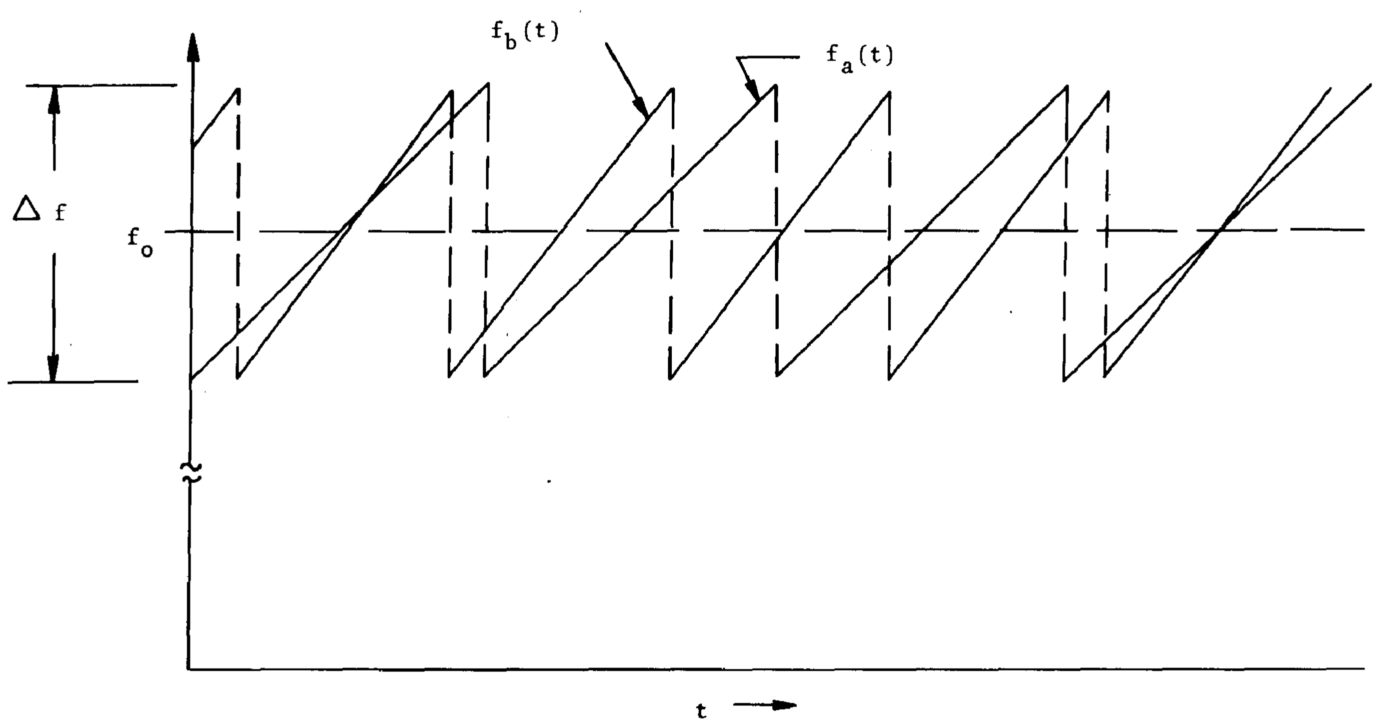


Figure 7-2 Instantaneous Transmitted Frequency As a Function of Time for Two Microwave Crash Sensors that are Frequently Sweep-Rate Coded

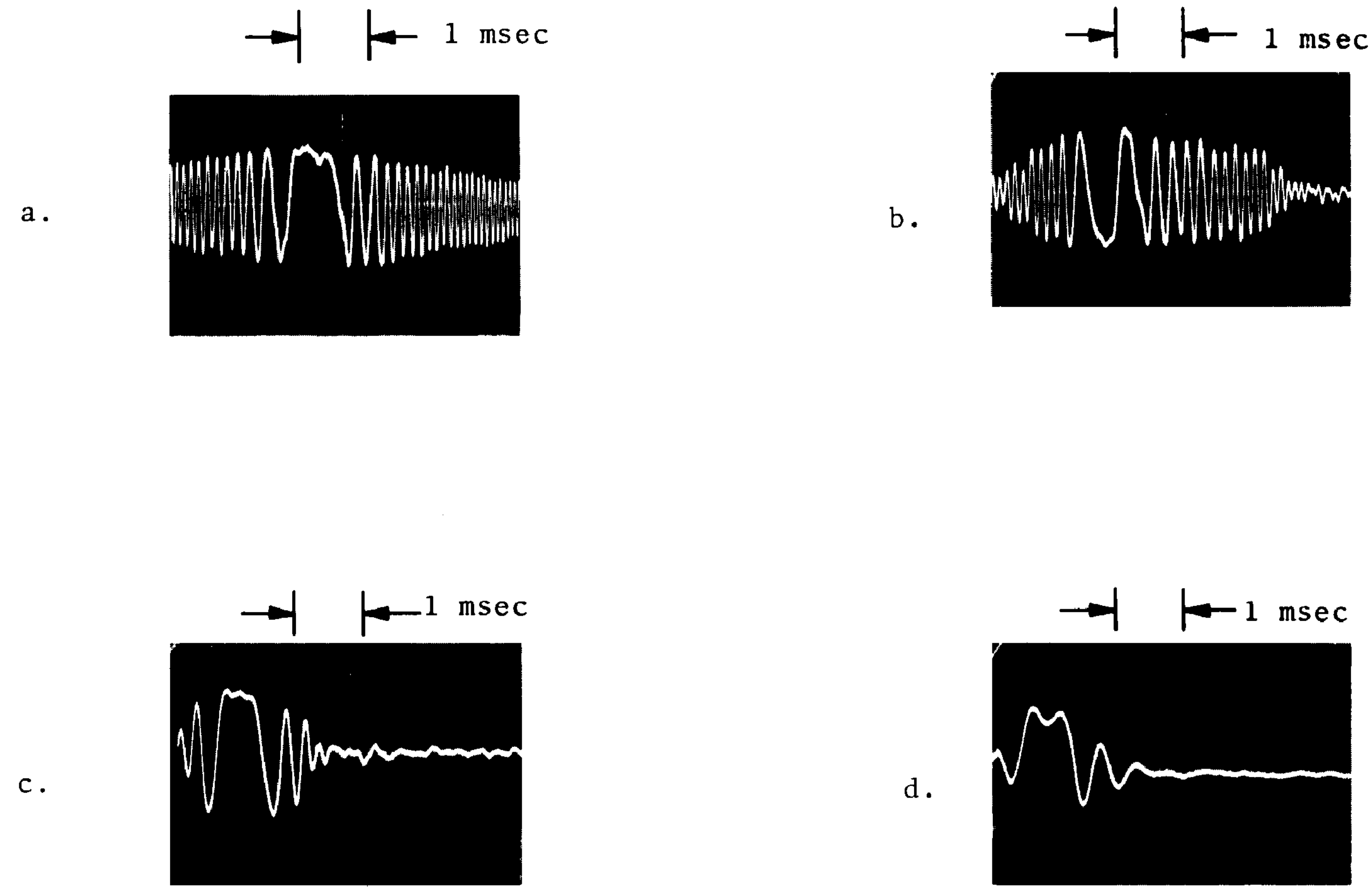
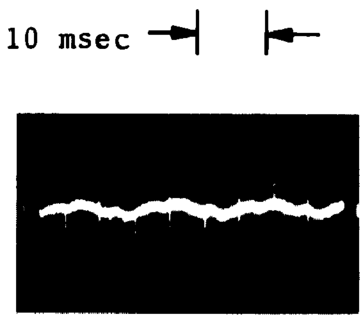


Figure 7-3 Beat Frequency Signals out of a Microwave Crystal Mixer After Low-Pass Filtering by Filter with Various Cutoff Frequencies

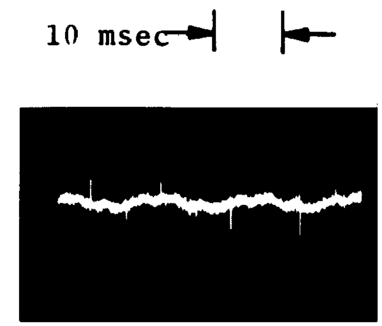
It is interesting to note the effect of filtering the crystal output signal by a low-pass filter with upper cutoff frequency f_{co}. The number of cycles of beat-frequency signal that fall below f_{co} is given approximately by the relation $N = 2 f^2_{co}/f'$. As f_{co} is lowered to 20 kHz, 10 kHz, and finally to 5 kHz, the number of cycles of substantial amplitude which pass through the low-pass filter is cut from many down to one pulse per crossing, as is shown in Figures 7-3b, c, d. The value of 1 pulse per crossing, with much smaller extra pulses on each side is viewed as the desirable maximum. This value corresponds to sweep rates no closer than 1 sweep per second. Figure 7-4 shows the filtered and unfiltered crystal output signals due to a fixed-frequency microwave signal beating with sawtooth-swept signals in which the crossing rates were 100 crossings/sec and 1000 crossings/sec respectively. Note that the signals after filtering either have a pulse rate that is too low or an amplitude that is too low to cause system actuation. This behavior was observed by use of the experimental set-up shown in Figure 7-5.

The effect on doppler signal properties due to the time-varying nature of microwave frequency is shown in Figure 7-5. As microwave frequency changes, the total number of wavelengths of radiation associated with the physical and electrical distance from transmitter, to target to receiving antenna, and back to the crystal mixer, changes. Where this total signal path length is L_{sig}, the change in number of microwave cycles in the system is $\Delta n = L_{sig} \Delta f/c$, where the speed of light $c = 3 \times 10^8$ m/sec. If

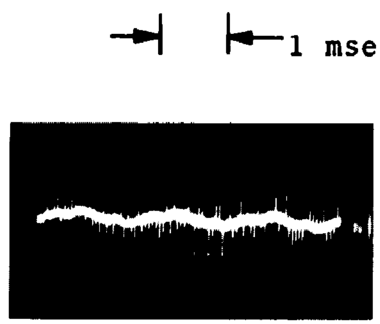
a.



b.



c.



d.

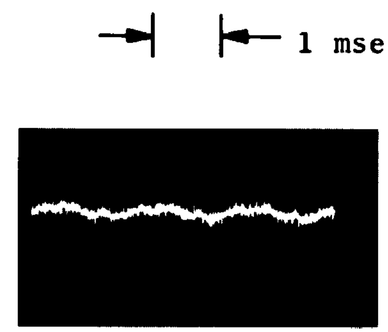


Figure 7-4 Beat Frequency Signals Out of a Microwave Crystal Mixer When Input Signals Are a 10.5 GHz cw Signal and a Sawtooth-Swept Signal Swept at a Rate of 25 MHz/sec with a Repetition Rate of 100 or 1000 Sweeps/Sec

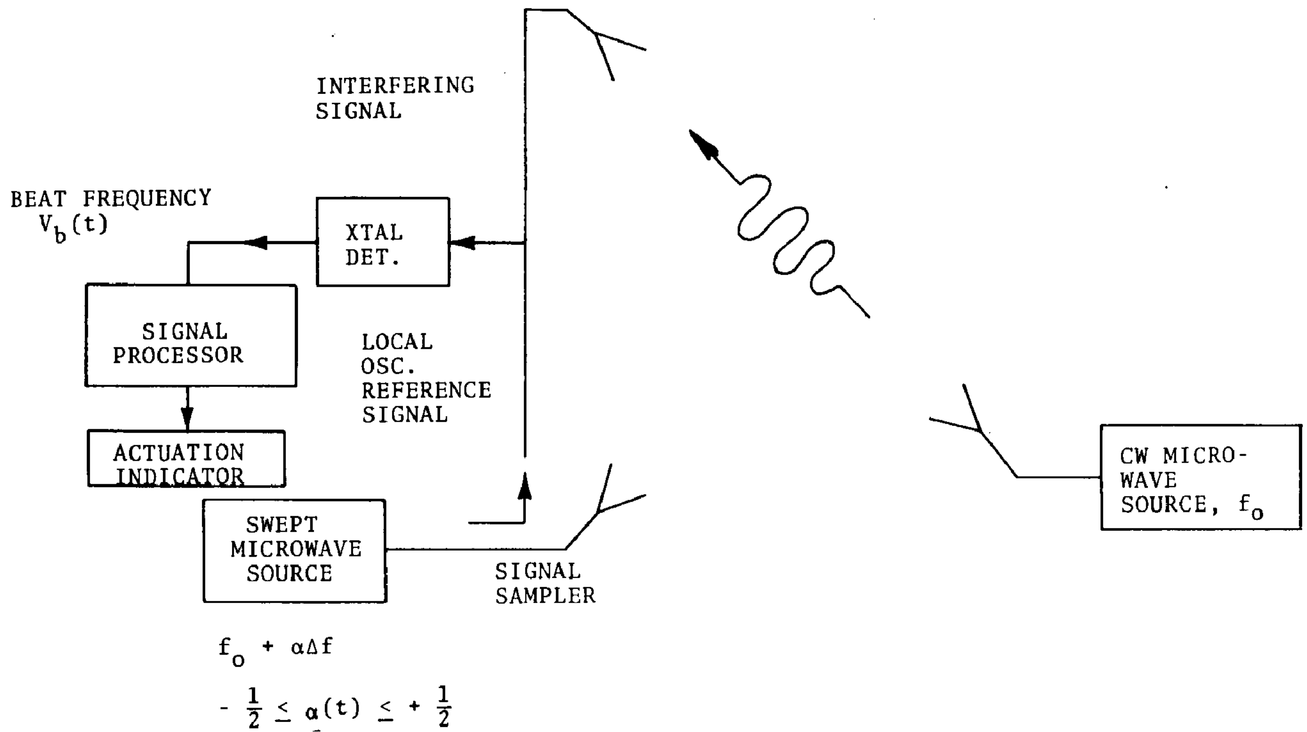
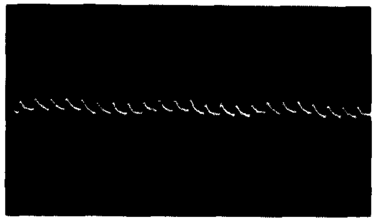


Figure 7-5 Experimental Microwave Circuit Used to Test for Reduced Interference Between Crash Sensor Systems by Means of Swept-Frequency Coding

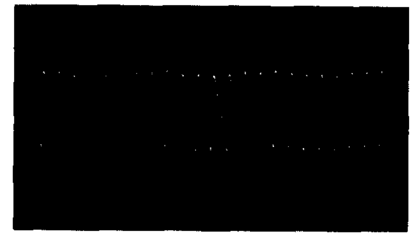
Δf is 25 MHz and L_{sig} is a few meters, Δn is a fraction of a cycle. Even a stationary target will therefore produce a time-varying doppler signal, since the relative phase of transmitted and received signals at the crystal mixer input will vary in time. This effect in seen in Figure 7-6. When the target moves, the relative phase between transmitted and received signals varies over complete cycles, producing larger amplitude fluctuations, as seen in Figure 7-6c. Low-pass filtering can then remove the high-frequency "dither" due to the sweeping of the transmitted frequency, leaving only the sinusoidal doppler signal as shown in Figure 7-6d.

The "averaging angle" θ_{avg}, which is the change in relative phase of transmitted and received signals due to the frequency sweeping, is given by the expression $\theta_{avg} = 2L_{sig}\Delta f/c$ radians, and is seen to increase as L_{sig} increases. The averaging angle is essentially the phase angle over which the doppler signals are averaged by the frequency-sweeping, phase-shifting, low-pass filtering process. This averaging over phase has the effect of attenuating the finally-emerging filtered doppler signal by the factor $[\sin(\theta_{avg}/2]/[\theta_{avg}/2]$. Thus as distance to target increases and L_{sig} increases and θ_{avg} increases, the filtered doppler signal decreases in amplitude more rapidly than would otherwise be the case. This effect was observed experimentally by recording the low-pass filtered doppler signal due to a moving target when various values of Δf were used. The signals shown in Figure 7-7 show that for Δf much above 25 MHz, there is a marked fall-off of sensitivity as range increases because of the

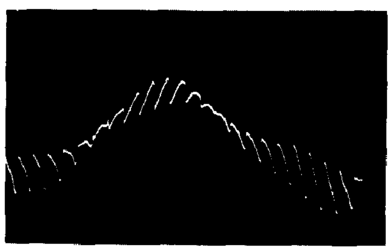
a.



b.



c.



d.

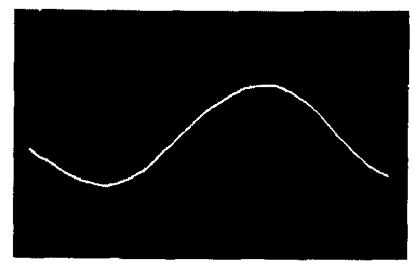
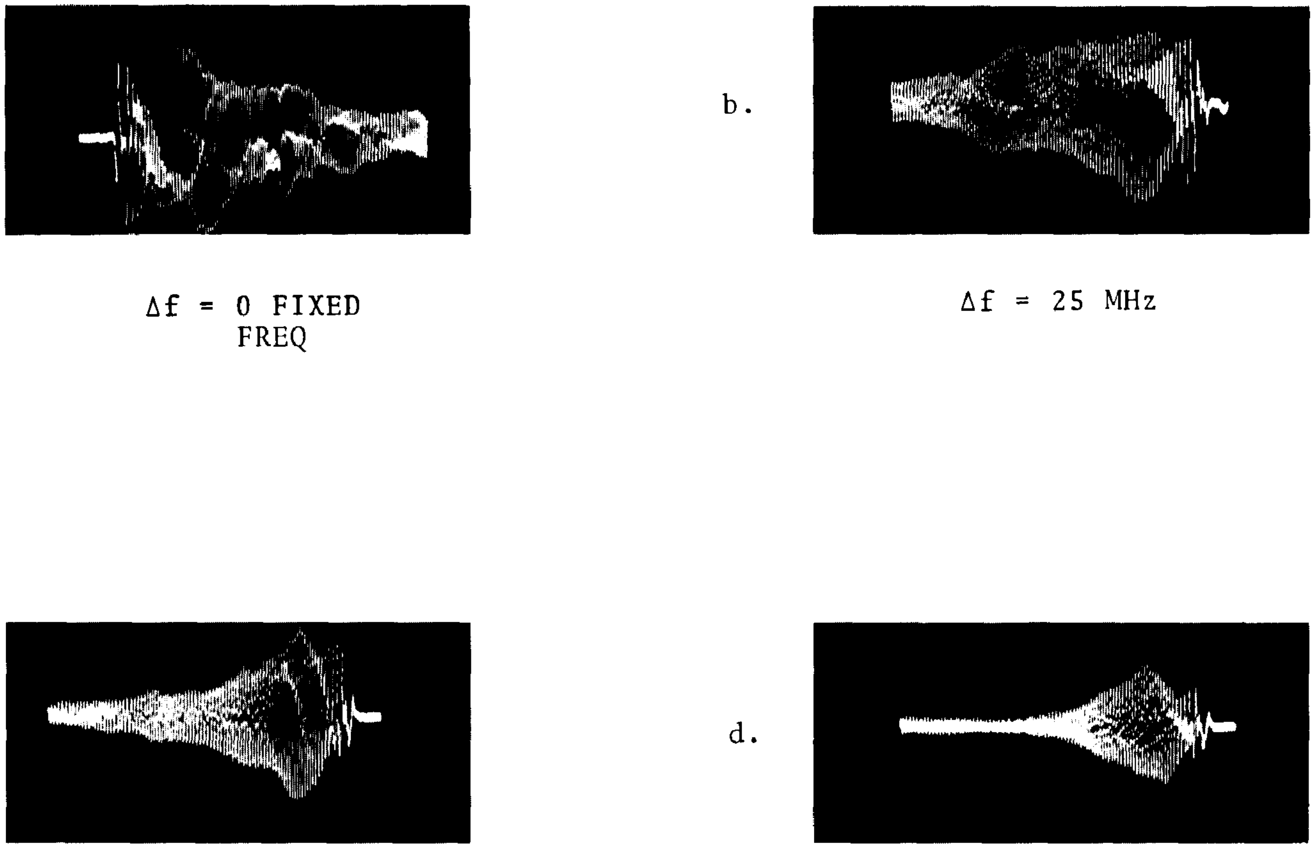


Figure 7-6 The Doppler Signals Produced In a Microwave Crash Sensor System in Which the Transmitted Signal is Swept in Frequency at a Repetition Rate Much Higher than the Maximum Doppler Frequency of Interest

a.

b.



Δf = 0 FIXED FREQ

Δf = 25 MHz

c.

d.

Δf = 50 MHz

Δf = 100 MHz

Figure 7-7 Doppler Signatures of Targets Showing Increasing Attenuation with Distance As Transmitted Microwave Frequency is Swept Over Increasing Wide Range phase averaging process. Therefore, it would probably be desirable to limit swept-frequency bandwidths to approximately 25 MHz to avoid decreasing sensitivity.

Theoretically, if all microwave crash sensors operated in the same 25-MHz band, and all used sweep rates for sawtooth frequency modulation across the band that were uniformly distributed in rate between, for instance, 20,000 sweeps/sec and 120,000 sweeps/sec, and the individual sweep rates were maintained at these exact integral numbers of sweeps per second, then the probability of interference between two automobiles encountering each other would be the probability that they had the same sweep-rate, multiplied by the probability that (given the same sweep rate) they had instantaneous frequencies within 5 kHz of each other. Thus, the probability for interference in a given encounter would be $(10^5 \times 2.5 \times 10^7/10^4)^{-1} = 1/(2.5 \times 10^8)$. And use of four such adjacent bands side by side to make up a total band of 100 MHz would reduce the probability to $1/10^9$.

Unfortunately, it is difficult to conceive of sweep rates being held with the rock-solid stability required to keep two signals with nominally the same sweep rate from "moving" in relative frequency and eventually crossing, thus negating the probability factor due to assumption of permanently fixed and separate relative frequencies. Thus, more realistically, one must assume that the decrease in potential interference can only be predicted on having available a large number of sweep rates. If one were to employ 10^6 different sweep rates spaced 1 sweep/sec apart with signals sweeping across one of four adjacent 25 MHz bands, then the probability of interference between two automobiles in a single encounter would be $1/(4 \times 10^6)$. Even this figure is maybe too high to be acceptable. Thus, rather than investigate use of still higher rates, a course that would involve major work in developing high-speed swept-frequency techniques, an alternative course was followed. (Additional motivation is the desirability of reducing the 100 MHz-bandwidth requirement.)

7.1.3 Frequency Modulation by Gaussian Noise Modulating Voltage

The results of the sawtooth frequency modulation work laid the foundation for a much more general look at the problem of using FM coding to reduce intervehicle interference. FM coding was shown to be compatible with the basic system concept, and in fact could be included as an "add-on" feature. After low-pass filtering of the doppler signal leaving the crystal mixer, doppler signals essentially had the same characteristics whether or not the microwave transmitted signal was frequency modulated, provided certain rules were followed. These rules were that frequency excursions must be limited to approximately 25 MHz maximum, and the modulation frequency must be a number of multiples of 5 kHz minimum so that the "dither" could be filtered out.

It was recognized that one prime failing of the sawtooth FM approach was that only one of the many possible modulating waveforms was employed. It was also seen that substantial benefits could be gained by using a large family of uncorrelated modulation waveforms. Then, for two microwave crash sensors to interfere, they would have to have approximately the same center frequency, and the same modulation waveforms. (More precicely, these factors would have to coincide more than some threshold amount.) It was decided that a very good choice of modulation waveforms would be band-limited Gaussian-noise-like waveforms. That is, the instantaneous transmitted microwave frequency would be equal to $f_0 + f_1(t)$, where $f_1(t)$ would be a random Gaussian function of time with zero mean, standard deviation σ_{f1} less than some fraction of 25 MHz, and spectrum lying between a number of multiples of 5 kHz and whatever upper limit could be easily attained or was needed. Subsequent calculations showed that σ_{f1} could have quite a small value--so small that frequency modulation could be demonstrated by directly applying a frequency modulation voltage in series with the dc bias voltage of a Gunn diode microwave source. (The Gunn diode microwave sources that were used in this work had a voltage frequency tuning rate of approximately 1.5 MHz/volt.)

Figure 7-8 shows the schematic diagram of the noise modulating system that was used. The basic Gaussian noise source was the amplified front-end noise of a quite noisy very high gain audio amplifier. A variable bandpass filter was used to tailor the spectral characteristics of the modulation voltage. Noise power was controlled by adjustment of the gain of the noisy amplifier.

In order to test the rapid tuning characteristics of the Gunn diode, a sinusoidal modulation signal was first employed. Figure 7-9 shows the resulting microwave spectrum. It is seen that the microwave spectral density replicates the probability density function of the sine wave. Figure 7-10 shows a band-limited Gaussian noise modulation waveform and the resulting

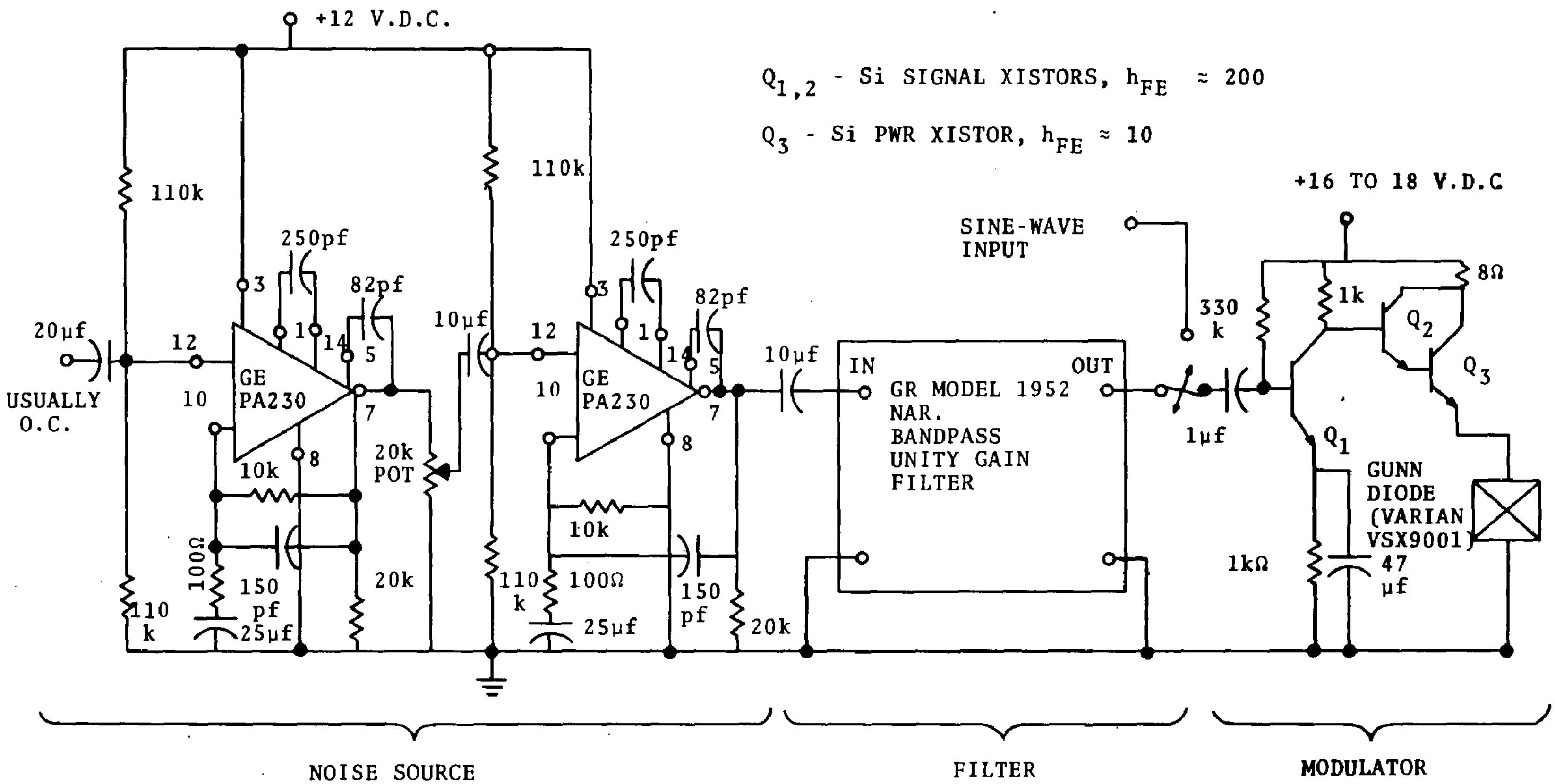
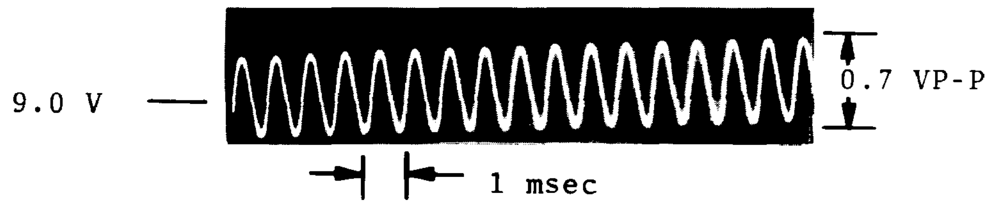
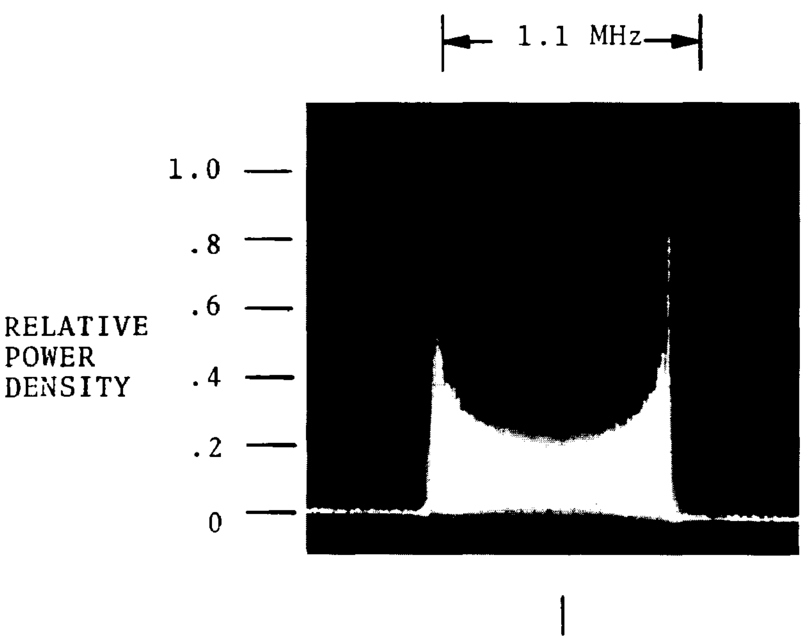


Figure 7-8 System for Noise-Modulating the Bias Voltage Applied to a Gunn Diode

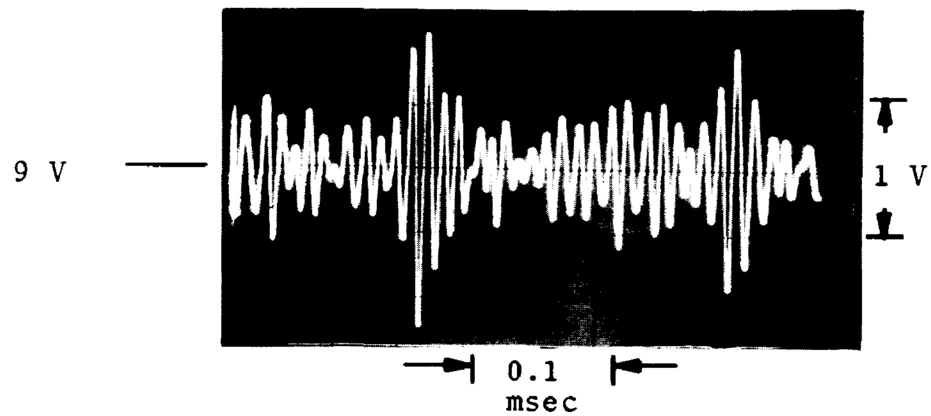


a. Bias voltage waveform as a function of time.

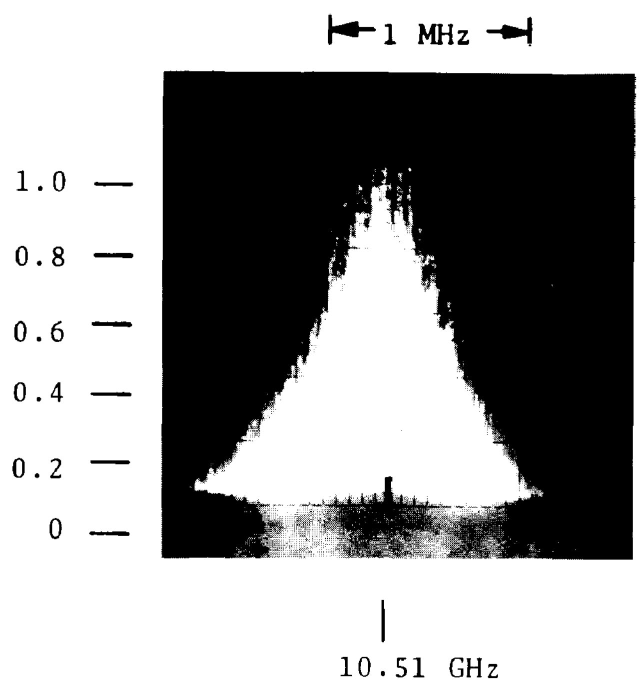


b. Resulting microwave power spectrum (linear vertical scale).

Figure 7-9 Sine-Wave Voltage Modulation of a Gunn Diode

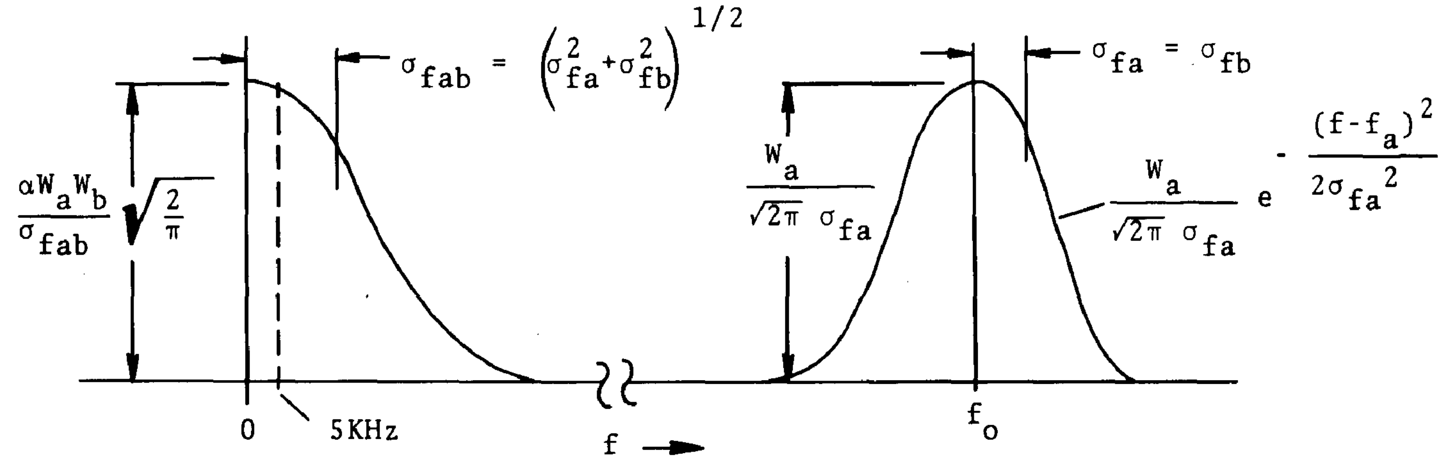


a. Bias voltage waveform



b. Microwave power spectrum (linear vertical scale)

Figure 7-10 Bandlimited Gaussian Noise Voltage Modulation of a Gunn Diode



Beat-frequency spectrum

Spectrum of Signal a or b

Figure 7-11a Signal Spectra When Noise-FM is Used -- One-Sided Density Spectrum at One Microwave Transmitter Signal, and Power Density Spectrum of Beat-Frequency Signal Due to Two Noise-Modulated Microwave Signals

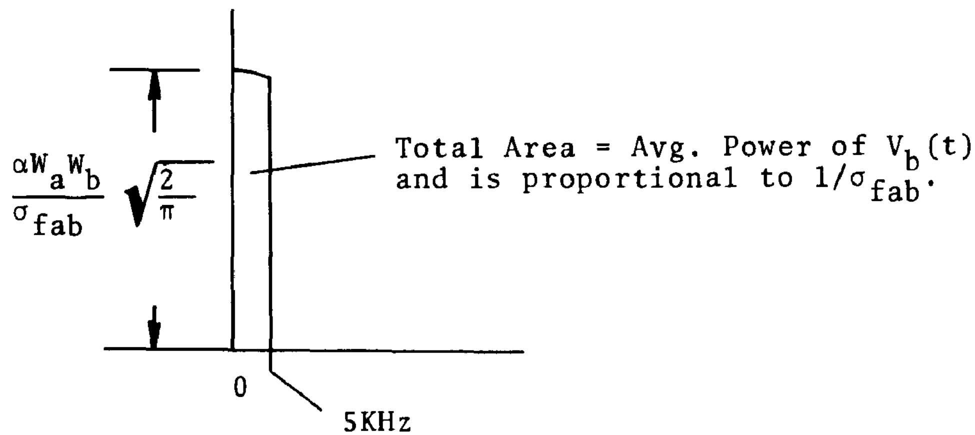


Figure 7-11b Signal Spectra When Noise-FM is Used -- Power Density Spectrum of Beat-Frequency Signal After Low-Pass Filtering

microwave power spectral density. Note the familiar Gaussian bell-shaped nature of the spectrum of the modulated microwave signal.

In analyzing exactly what was accomplished by use of the noise-like FM, it was determined that this technique would cause identical microwave crash sensor systems to appear to each other as broadband Gaussian microwave noise sources. Thus, even if two microwave crash sensors had exactly the same transmitter center frequency f_0, the probability of the two signals being within 5 kHz of each other for significant amounts of time would be quite small. The fact that one system's signal looks like Gaussian noise to another system depends upon the fact that at any instant of time, the beat-frequency signal (following low-pass filtering) can be regarded as the sum of (b/5000) statistically independent random variables, where b is the spectral width of the modulating voltage. Further, the sum of many statistically independent randome variables with equal mean values and standard deviations is approximately Gaussian, independent of the specific probability density function of the separate random variables.

Figure 7-11 depicts the power spectral density function of either of two crash sensor microwave transmitters a or b. Also shown is the power spectral density function of the beat-frequency signal before and after low-pass filtering by a 5 kHz low-pass filter, for the worst possible case where $f_{0a} = f_{0b}$. The low-pass filtered beat frequency signal $v_b(t)$ will be a bandlimited Gaussian noise-like waveform whose average power is proportional to $1/\sigma_{f1a} = 1/\sigma_{f1b}$.

It can be shown that the average rate of positive level-crossings of a threshold level v_0, by the signal $v_b(t)$, whose mean squared amplitude (proportional to average power) is $\overline{v_b^2} = \sigma_{vb}^2$, is given by the expression

$$n_{v0} = (1/3)^{1/2} f_{co} \exp(-v_0^2/2 \sigma_{vb}^2) = 2{,}890 \exp(-v_0^2/2 \sigma_{vb}^2)$$

for the case f_{co} = 5 kHz.[17] Then, assuming that the system will only be employed if $v_b(t)$ crosses the threshold v_0 very rarely, the Poisson probability law can be shown to apply,[18] giving a probability of N positive level crossings in time τ equal to

$$P(N,\tau) = [n_{vo}\tau)^N/N!] \exp(-n_{v0}\tau).$$

It is easily shown that for very small values of $n_{v0}\tau$, the probability of there occuring 16 or more positive level-crossings of v_0 in the τ = 36 msec recycling time of the crash sensor doppler cycle counter, sufficient to trigger the system, is approximately equal to the probability of there being exactly 16. And thus the average rate of false alarms under continuous exposure is approximately

$$R_{fa} = \frac{P(16, .036 \text{ sec})}{.036} = 1.3 \times 10^{-12} (n_{v0}\tau)^{16} \exp(-n_{v0}\tau)/\text{second}.$$

If it is desired to have a false alarm rate from constant exposure to an interfering signal as small as $R_{fa} = 1/10^6$ years, the corresponding mean number of beat-frequency counts above threshold in each 36 msec period is $n_{v0}\tau = 0.83$. This value corresponds to a value of RMS beat frequency signal out of the 5 kHz low-pass filter of $\sigma_{vb} = 0.25\ v_0$. Realistically, these calculations must be interpreted by observing that because of the exponent 16 in the relation for R_{fa}, there is a very sharp threshhold separating those values of σ_{vb} that essentially never lead to false triggering from those values of σ_{vb} that lead to incessant triggering.

This behavior was observed while conducting the experiment depicted in Figure 7-12. In this experiment, a fixed-frequency microwave source played the part of the interfering signal, and the Gunn diode corresponding to the microwave crash sensor signal source was Gaussian noise frequency modulated. The Gaussian noise modulating voltage was band-limited between 4 and 60 kHz. The fixed-frequency microwave source was a microwave sweep generator operated at fixed frequency. The microwave tube, a backward-wave oscillator, was quite unstable, and had an RMS frequency deviation σ_{fb} of approximately 50 kHz. The Gunn diode was inherently much more stable, and its RMS frequency deviation σ_{fa} was determined by the noise modulation signal.

The experiment that was performed started with adjustment of the average frequency of each microwave source to as nearly the same value as possible with no noise modulation. Then, the microwave power into the crystal detector from the interfering signal was increased until the test crash sensor system began to actuate. It was observed that a power level change of a very few dB resulted

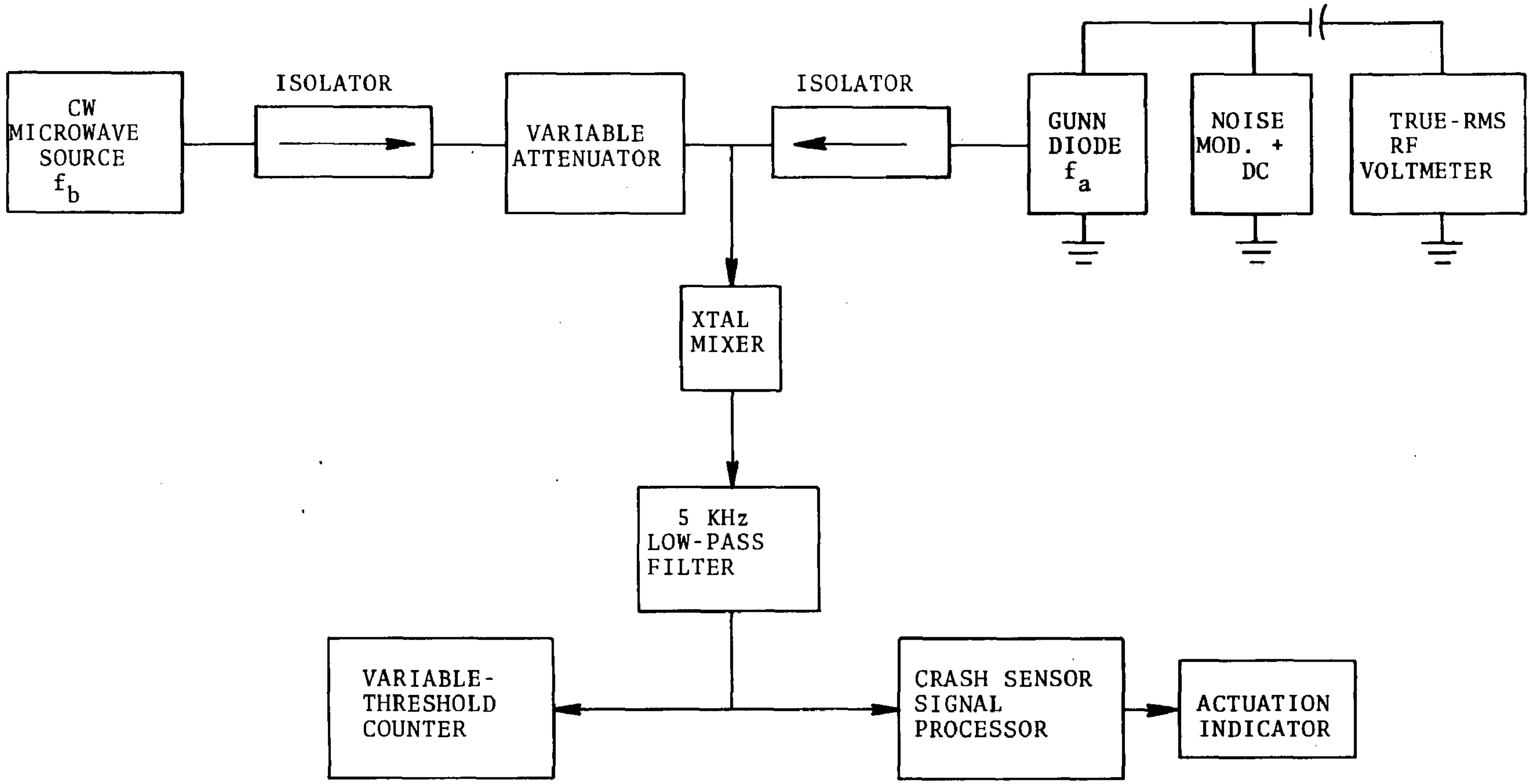


Figure 7-12 Microwave Circuit Used to Investigate Interference Reduction Due to Use of Noise-FM

in a change from incessant actuation to essentially no actuation whatever. Then, increasing amounts of noise modulation signal were applied to the Gunn diode, leading to increasing values of σ_{fa}, and increasing values of frequency difference standard deviation $\sigma_{fab} = (\sigma_{fa}^2 + \sigma_{fb}^2)^{1/2}$. The amount of increased microwave power from the interfering source required to just cause triggering was noted, and the resulting relationship between reduced sensitivity and RMS frequency difference is shown in Figure 7-13.

Note that the curve shown in the log-log plot has approximately unity slope; i.e., an increase in σ_{fab} by a factor of 10 results in a reduction in sensitivity by approximately 10 dB, or a factor of 10 in power. The Gunn diode was incapable of being modulated with RMS frequency deviations of greater than 2 MHz. However, extrapolating the results obtained to the probably desirable desensitivity value of 20 dB indicates that the required RMS frequency difference is approximately 3.5 MHz. This value corresponds to the case $\sigma_{fa} = \sigma_{fb} = 2.5$ MHz, the probable figure to seek in developing production units especially for this application.

7.1.4 Conclusions

It has been demonstrated that very simply implemented coding techniques can be used to reduce intervehicle interference between automobiles equipped with microwave crash sensors to acceptable levels. The techniques available for this purpose are completely compatible with the remainder of the microwave crash sensor system. It has been demonstrated that a simply derived band-limited Gaussian noise voltage is suitable for use as the frequency modulating signal.

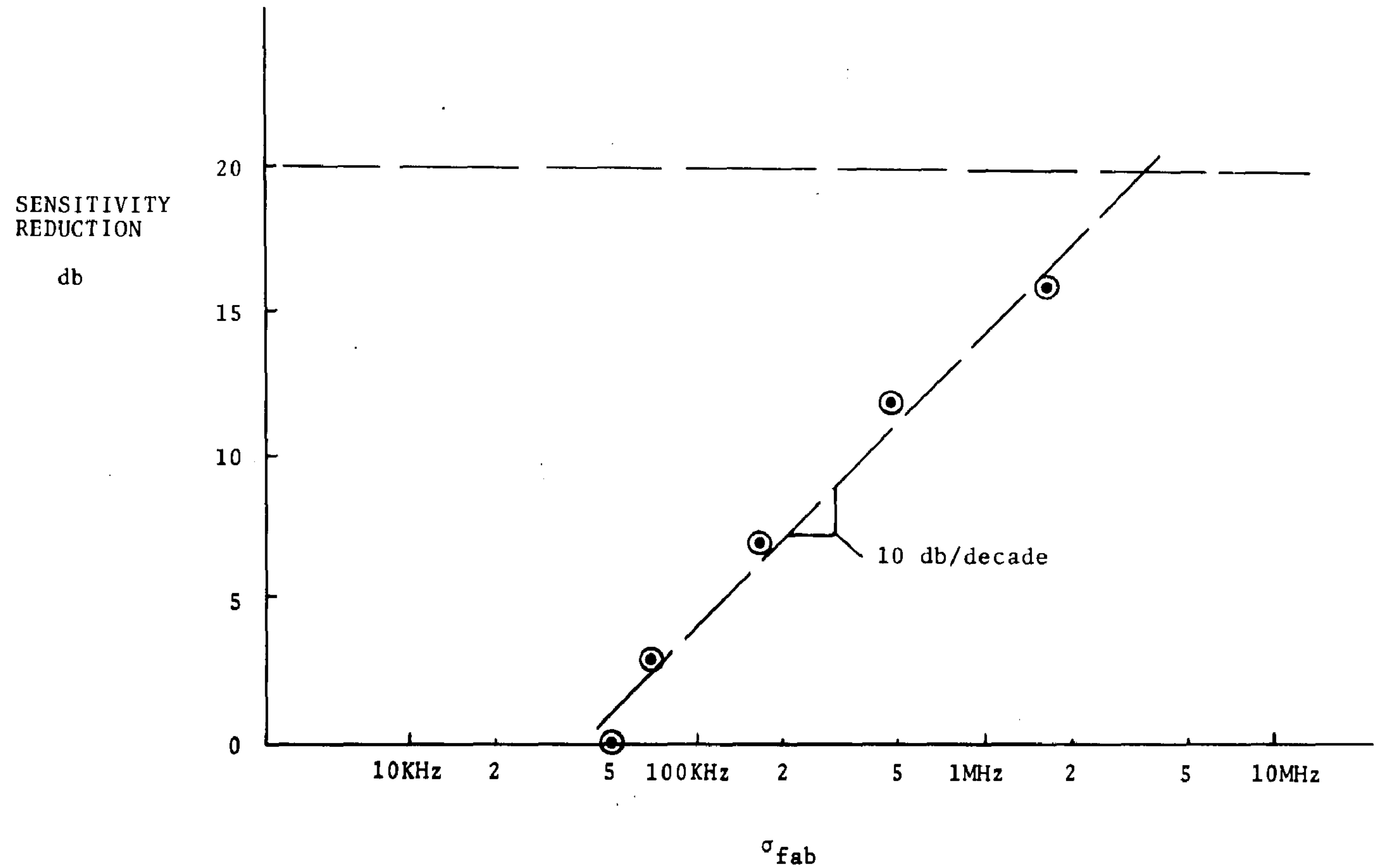


Figure 7-13. Reduction In Sensitivity to Actuation of Microwave Crash Sensor As a Function of Standard Deviation of Transmitter Difference Frequency

$$\sigma_{fab} = \left[(f_a - f_b)^2\right]^{1/2}$$

In practice, it may be more desirable to use other techniques for generation of the random modulation signal, such as the generation of digital noise followed by D/A conversion, or through the use of pseudorandom codes stored in shift registers followed by D/A conversion. These techniques may be called for because of the unpredictable noise characteristics of active linear semiconductor devices. At any rate, the principle of operation could be essentially the same, with desensitivity to interfering signals attained being directly proportional to the spectral width of microwave signals utilized.

[The modulation and coding techniques considered in this study often go under the heading "Spread-Spectrum Techniques." These techniques are frequently discussed as possible means of constructing radars that are difficult to jam.[19] In practice, however, the techniques become somewhat unwieldy due to the fact that tapped delay lines must be used to delay the coded local oscillator signal the same amount of time that it takes for the radar signal to reach the target and return. This must be done so that the returning signal can be correlated with the signal that was transmitted to sort out unwanted jamming signals. In the case of the microwave crash sensor, that time is so short (appx. 10^{-8} sec), that the delay line is negligibly short and can be omitted.]

7.2 RADIATION HAZARDS

7.2.1 CW Systems

All civilian microwave systems are currently receiving close scrutiny with respect to possible hazards to human health. While the low transmitter powers involved here suggest that such problems should be minimal for the crash sensor, the possibility of risk to traffic controllers, tollgate attendents, and garage, service station, and parking-lot personnel, who may receive almost continuous exposure for many hours per day, warrants careful consideration.

Determination of the maximum level of electromagnetic radiation which will pose no threat to human health is a subject currently enmeshed in a certain amount of controversy. The most-nearly comparable case is that of microwave ovens, which also are for use by or in the vicinity of the entire population, with no special training or precautions assumed. In that case the HEW standard is a maximum radiation density of 1 mW/cm^2, at a distance of 5 cm, for units as manufactured, with no allowable degradation in use beyond 5 mW/cm^2.

In TSC experimental systems, microwave sources with total power of 25 to 50 mW have been used with no difficulty, and 10 mW appears to be completely feasible for this short-range application. At 10 GHz, antennas appropriate to the application have an area of approximately 40 cm^2, so that if one allows a factor of two variation in power density across the antenna, the maximum intensity at that surface will be .5 mW/cm^2, comfortably within the standard for new ovens.

Assuming a beamwidth of 25° by 35°, the density at a range of one meter is down to approximately .004 mW/cm^2, well under even the Russian standard for continuous exposure, generally regarded as a conservative guideline. Further, it appears that successful operation can be obtained with substantially lower power if necessary, although system circuit noise would be a greater problem. If is also quite possible that - for both this reason and interference considerations - practical systems will be turned off whenever the vehicle is stationary, thus avoiding any possible hazard to automobile mechanics, pedestrians at intersections, etc.

These conclusions are relatively independent of operating frequency except in the immediate vicinity of the transmitting antenna. Operation at 35 GHz, for example, would involve antenna dimensions smaller by a factor of 3.5, or approximately one-tenth the area. For this case the above figure of .5 mW/cm^2 becomes 5 mW/cm^2, requiring that the necessary special efforts be undertaken to utilized lower transmitter power.

7.2.2 Pulsed Systems

Pulsed systems involve in their operation extremely low average radiated power, due to the very short duty cycle. In addition, the short range and relatively low sensitivity required of the system, and the wide antenna patterns typically associated with pulsed techniques, permit modest instantaneous power levels, as well.

8. SUMMARY AND CONCLUSIONS

8.1 INTRODUCTION

The research described in this report has the objective of delineating the preferred means, potential effectiveness, and estimated costs of carrying out anticipatory sensing of automobile collisons. A simple analysis indicates that the intended application - actuation of passive restraint systems - requires a sensing distance of only one to two meters in front of the vehicle to extend the protection of such safety devices to impact speeds of 30 to 60 MPH - a range encompassing a large number of fatal and severe-injury accidents. Examination of the possible means by which this function might be realized has led to the conclusion that radar represents the most promising crash sensing technique, and can be characterized by low cost and acceptable performance.

8.2 TECHNICAL SUMMARY

The research described in this report provides substantial evidence as to the effective performance and low costs which can be associated with radar crash sensing. Actual implementation of this technique on a large scale would, of course, warrant a substantial product development effort to provide a more nearly optimum realization. Alternative techniques, such as short-pulse methods, would be worthy of equal consideration. However, the basic conclusions are unlikely to be significantly changed. In terms of electronic performance, serious problems are anticipated.

Given explicit actuation criteria in terms of frequencies, amplitudes, and time intervals, it has been found that triggering can be nearly guaranteed when warrented, and inadvertent actuation can be made an extremely rare event.

Modern microwave technology is capable of providing compact, extremely durable antennas at a modest price, and solid state oscillator and receiver components pose no major problems. The recent development of large scale integrated circuits makes possible sophisticated and redundant signal processing which provides extremely high reliability - more than adequate with respect both to non-operative and unwanted actuation failure modes. Fabrication, packaging, and power conditioning consistent with automotive use is not a large problem, having already been largely overcome for other systems. Malicious unwarranted activation by vandals can be made quite unlikely, as triggering by radar alone can occur only for a combination of high vehicle speed and a physically large target in the correct location. The primary constraint on the potential effectiveness of radar sensors is the limited correlation between obstacle lethality or hazard, and radar reflection coefficient. However, this weakness should not be over-emphasized. To a large degree, the more severe targets - automobiles and concrete walls - provide a satisfactory radar signal. The corners of cars, which give low signals, generally are "softer" targets, of reduced hazard, and so need not occasion major concern. Trees and telephone poles are the most serious potential "misses", although they fortunately comprise a relatively small number of accident objects.

These weaknesses strongly suggest that radar (anticipatory) sensing is desirable only for the cases of vehicle size and impact speeds for which existing mechanical and electromechanical sensors cannot provide sufficiently early deployment. Thus, the only sensor system configurations which are viable are those hybrid forms for which impact sensors are used up to the maximum feasible speed, at which point radar is added. The use of an intermediate range, depending upon radar sensing plus a very rapid but indiscriminant impact confirmation, appears promising but may apply to a speed range so small as to be not worth the added complication. Similarly, the desirability of a dual (four antenna) system must be determined by more elaborate studies, assuming that a CW technique is, indeed, optimal. This and other studies suggest that considerations of both performance and economics imply that CW systems in the frequency range of 10 - 25 GHz are preferable, although operation as high as 35 GHz may be feasible.

The commonality of certain power conditioning, interconnection, signal processing, and diagnostic functions in both impact and radar sensors makes possible some reduction in the incremental cost associated with the use for anticipatory sensing in addition to electromechanical devices. Thus, the overall estimated OEM radar crash sensor cost of approximately $20 is considered to be realistic. However, various multipliers associated with bringing such a device to the automobile showroom floor, and paying for and maintaining it, lead to an approximate societal cost in the range of $75 to $150 per vehicle, or $.75 to $1.5 billion total annual cost, assuming all cars to be so-equipped.

Very approximate effectiveness calculations have suggested that the potential benefits of full implementation, conservatively estimated, are preventation of approximately 5000 or more deaths and and least 200,000 serious injuries each year. If injuries are taken to be approximately one-thirtieth as costly to society as fatalities, an annual total expense of $1.5 billion implies a cost of the order of $130,000 to save each life, and $4000 to prevent a serious injury. Determination of "acceptable" costs is not a part of this study, but it should be noted that these figures are significantly less than are often used as cost/benefit criteria.

8.3 OVERALL ASSESSMENT

The above summary indicates that radar anticipatory collision sensing represents a technically feasible automotive safety subsystem which can prevent death and injury at a cost consistent with that of other systems which have been deemed acceptable, such as improved structures or basic passive restraints. However, a conclusion as to the ultimate viability of anticipatory sensing is not possible at this time. A number of uncertainties - largely non-technical - must first be resolved.

Perhaps the most crucial is the ultimate effectiveness and acceptability of passive restraint systems, particularly in high-speed collisions. Deployment in (for example) a 50 MPH (barrier equivalent) impact will be of value only if the vehicle exhibits sufficient structural crashworthiness to permit survival. In addition, the need for anticipatory sensing, rather than impact crash detection, is a function of sensing time, necessary deployment interval, and vehicle dimensions. Thus, factors such as the mix of compact and subcompact cars in the general automotive population become relevant. (Note that this element is at present subject to conflicting forces such as reduced energy consumption and improved crashworthiness.) The future accident spectrum is also an important variable, both in terms of impact velocities and objects struck. These factors can only be approximated very crudely at present, and insufficient basis exists to warrant extrapolation for the future.

Relevant technical factors involve the possibility of development of alternative techniques - restraint systems capable of very fast deployment, and more rapid crash sensors, possibly associated with energy absorbing bumpers. Reduction of the total deployment time budget to 15 - 20 msec would limit the value of anticipatory sensing - particularly for larger cars - to the point that it might be deemed uneconomic.

Thus, a variety of ambiguities, plus the very substantial amount of further research and final product development that would be required, make clear that anticipatory sensors are - at best - a "second generation" system element, not relevant to improved occupant protection until the late 1970's in any event. Further, continued research in this area should be postponed pending more definite results as to the effectiveness of deployable restraints and vehicle structures at higher speeds, the percentage of accidents actually occuring with barrier-equivalent impact velocities in that range, and the limits of impact-sensing systems.

8.4 INADVERTENT ACTUATION

Inadvertent actuations - false alarms - have received considerable attention in discussions of both impact and anticipatory sensors, largely due to the dramatic vision often conjured up. Experience to date suggests that, in fact, the consequences of such an event will rarely be more serious than the cost of refitting the system. However, an extremely low false alarm rate remains highly important to initial public acceptability, well past the level of economic relevance. (This factor may be rather more important for restraints designed for very rapid deployment.) Insofar as electronic circuitry is concerned, no problem is envisioned in attaining a negligible probability of occurrance. The question arises only in connection with collision with trivial, non-hazardous objects. The most serious of these appears to be a sheet of water, as might be thrown up by a nearby vehicle. Although this difficulty is amenable to treatment, it will require careful consideration, for water is a good microwave reflector. Aside from this case, there are few, if any, obstacles which have a significant return but do not represent some "real" collision, even if deployment is not truly warranted; there is to some degree a semantic question in defining "inadvertency". Also, recall that radar actuation can occur independently only for high closing rates. Although statistics on "non-collisions" are lacking, experience suggests that motorists typically encounter very few such high-speed minor collisions without actually being involved in an accident. This topic clearly justifies further study. However, it should be noted that the problem is more closely related to possible public apprehension, which should dissipate when passive restraints become common, than to any actual threat to personal safety or economic loss.

8.5 IMPLICATIONS OF GENERAL USAGE

Two primary concerns arise when one considers the possibility of widespread installation of radar collision sensors. The first - potential radiation hazard - has been found to be trivial; in addition to the very brief short-range exposures one can actually imagine occurring, the radiated intensity at the antenna can be reduced to a level meeting very conservative standards for continuous exposure (at least an order of magnitude below the allowed values for microwave ovens).

The problem of various kinds of detrimental interaction between adjacent radars has required a substantially greater amount of study. However, the extremely short-range, high-threshold nature of the system, combined with the broad-beamwidth antenna patterns involved, have been shown to permit even a possibility of interference only at very short range - two to three meters. A thorough examination indicates that various forms of frequency modulation over a very narrow band will prevent any possibility of inadvertent actuations from this cause, and signal levels do not approach values for which serious "blinding" or overloading can occur. In general, one can expect gated short-pulse systems (not explicitly studies in this program) to exhibit even greater resistance to interference problems, and to involve a truly negligible radiated power.

8.6 IMPLEMENTATION CONSIDERATIONS

It has been indicated that radar anticipatory sensing offers, at a moderate cost, significant effectiveness with no severe disadvantages. Whether it is either the only solution, or the one most nearly optimal, to the problem of occupant protection for high-speed collisions, particularly for smaller vehicles, cannot be determined at present. However, even an affirmative finding in this regard would give rise to very challenging problems if one attempts to include anticipatory crash sensing in the regulatory framework. Performance specifications for non-predictive passive restraint systems are relatively straightforward, although not without some difficulties in defining compliance test procedures. However, when a barrier must simulate not only the crash characteristics of real-world obstacles, but also the radar response, serious problems arise. Thus, an attempt to write functional or performance specifications, compatible with a reasonable compliance test, is frought with difficulties. Objects with very similar collision attributes, and even appearance, can differ markedly as perceived by radar, and the response of different anticipatory sensors to the same target may be quite varied. Selection of a specific set of "test obstacles" would almost certainly encourage designers to construct systems tailored to the test, possibly to the detriment of operation under more typical circumstances. Similar problems arise in seeking an economically reasonable test of resistance to inadvertent firings. While one might attempt merely to specify actuation criteria merely in terms of position, closing rate, and radar cross-section, it would be most difficult to avoid specifications which were dependent upon a particular technique or manner of construction. Such an approach would also limit the incentive to seek to use signature analysis or supplementary sensing means. Alternatively, an attempt to specify a particular system design would freeze the technology and lead to virtually endless debate and controversy over the exact nature of the mandatory design. Serious liability implications would also be involved, in the event of failures tracable to basic concept. There are, however, two alternative possible avenues by which such systems might come into use:

a) Voluntary - Given that passive restraint systems prove both acceptable to the public and highly effective in injury prevention, and that predictive sensing need not add excessively to the restraint system cost, the very dramatic improvement in overall system effectiveness, due to extension of protection to higher speeds, could be attractive as a sales feature, particularly if strongly encouraged by DOT, the insurance industry, and safety and public interest groups.

b) Quasi-Mandatory - A simple extension of the required speed for which basic crashworthiness must be demonstrated - possibly to 50 or 60 MPH - could leave a manufacturer with the choice of anticipatory sensing or a rather expensive high-speed mechanical sensor and aspirated rapid inflation system. It is quite possible that radar would prove both more effective and of lower cost. One would then have to rely on corporate responsibility and legal/liability considerations to ensure that overall system performance was satisfactory.

8.7 TOPICS FOR FURTHER RESEARCH

As suggested above, final system optimization must await better definition of performance specifications, application constraints, and overall potential value. The time scale involved does not appear to require that high priority be accorded such tasks at present. However, certain topics which warrant further attention can be identified.

8.7.1 Alternative Radar Concepts

This study has concentrated upon bistatic CW doppler radar as a simple and convenient concept, suitable to both experimentation and actual application. However, other techniques, such as "binaural" range-gated ultra-short-pulse radar, may potentially achieve a higher level of performance with only limited increase in cost and complexity, if any. Such alternatives warrant further consideration.

8.7.2 Analysis of Collision Conditions

Determination of optimal sensor characteristics and evaluation of potential effectiveness depends upon more precise information than now exists concerning obstacles, impact angles, barrier equivalent speeds, and other crash parameters.

8.7.3 Target Discrimination

As stated earlier, considerably more information can be acquired with radar than is utilized by crash sensors constructed to date. Other researchers have drawn attention to the potential benefits of comprehensive radar signature studies, aimed at improved discrimination between hazardous and non-hazardous obstacles. A small computer would presumably be necessary for implementation of this approach, but advances in solid state technology permit this possibility.

8.7.4 Hybrid Systems

Utilization of sensing means additional to also can significantly mitigate discrimination problems. This study has suggested addition of bumper-mounted impact switches for intermediate speeds, and others have pointed out potential benefits of lasers for determination of target size. However, there has been no large-scale effort to explore either the technical feasibility or operational effectiveness of such concepts.

8.7.5 Operation in a Realistic Environment

Although a number of research groups have tested anticipatory sensors under normal (and abnormal) conditions, implementation of such devices will require a lengthy and full-scale test, involving fleet installation with appropriate recording devices.

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APPENDIX A

RADAR SENSITIVITY

A.1 GLOSSARY

a	Antenna gain ratio at the point (x,y), relative to maximum gain, at centerline of beam	
A	Antenna gain measured at the point (x,y) $A \equiv 10 \log_{10}(a)$	dB
A_0	Antenna beam distribution constant	dB
L	Distance between receiving and transmitting antennas, along the x axis	meters
R	The path length from antenna to target	meters
s	Signal strength at receiver from target at the point (x,y)	watts
s_{max}	Maximum possible received signal (for target placed at the point giving the largest received signal)	watts
s_0	Signal strength at transmitter	watts
S	Received signal strength from target at the point (x,y) $S \equiv 10 \log_{10} \left[\frac{s}{s_{max}}\right]$	dB
S_M	Constant minimum signal loss	dB
x	axis along front of vehicle	meters
y	Axis in direction of travel	meters
α_H	Half-power beam width	radians
α_0	Antenna beam distribution characteristic angle	radians

β	The angle to the antenna centerline, measured from straight ahead	radians
θ	The angle to the point (x,y) measured from straight ahead	radians
$\emptyset$	Beam distribution angular function (not physically realized)	radians

Note: Subscripts T and R are used to refer to transmitter and receiver, respectively.

A.2 THE BASIC RADAR SYSTEM

The basic radar system is shown in Figure A-1. The front of the vehicle defines the x axis, with transmitter located at x = 0 and receiver located at x = L. The y axis extends forward of the vehicle from the transmitter position such that the transmitter is located at y = 0. The target is located at any point (x,y). The paths from transmitter and receiver to the target are R_T and R_R, respectively.

$$R_T^2 = x^2 + y^2 \quad (1)$$

$$R_R^2 = (L - x)^2 + y^2 \quad (2)$$

The angles which the target paths make with the straight-ahead axes are θ_T and θ_R, respectively.

$$\theta_T = \tan^{-1} \left(\frac{x}{y} \right) \quad (3)$$

$$\theta_R = \tan^{-1} \left(\frac{L-x}{y} \right) \quad (4)$$

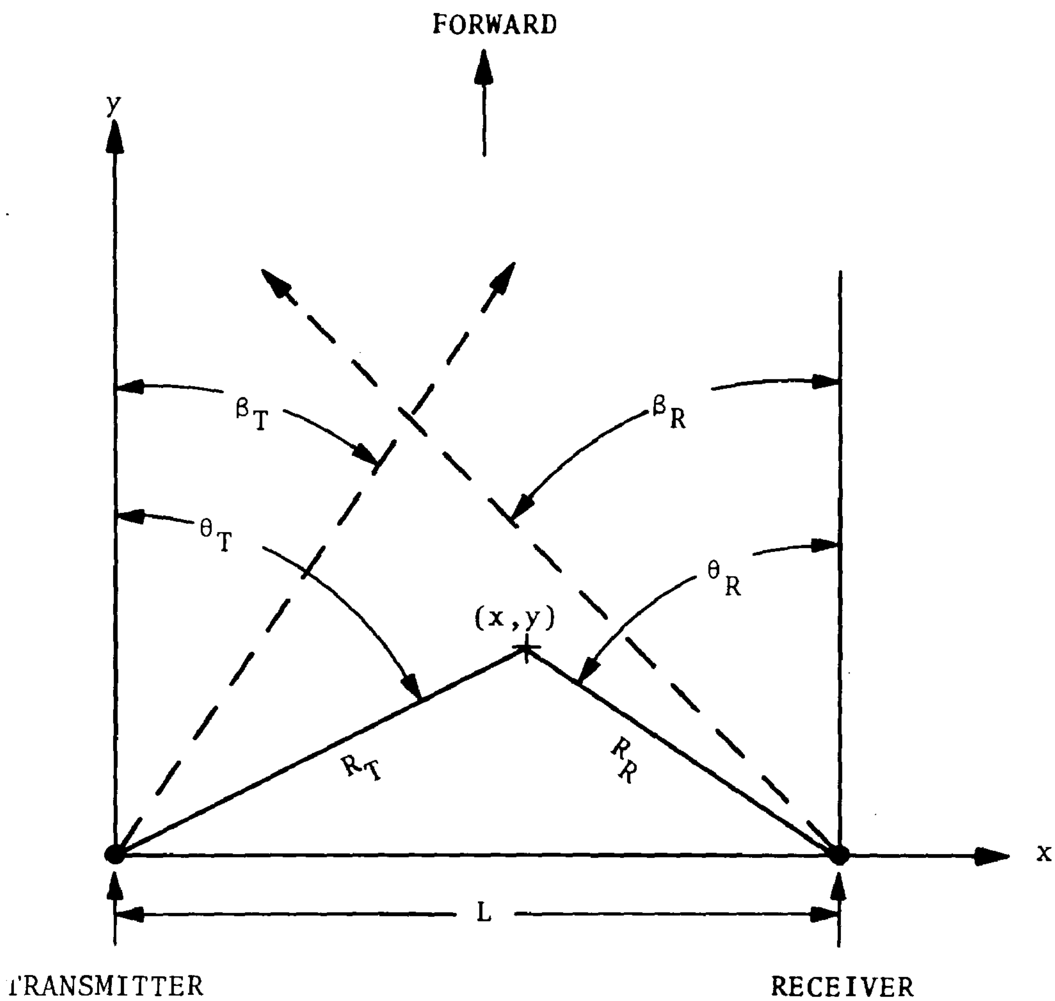

Figure A-1 Basic Radar System

The antennas are adjusted so that they are aimed inward, i.e. the beam centerlines make angles of β_T and β_R, respectively, with the straight-ahead axes.

Each antenna will have its own radiation characteristics, such as beam width and gain distribution, which shall be described in Section 4. However, at any point (x,y) each antenna will have some value of gain, in dB, which shall be labeled A_T (transmitter) and A_R (receiver). In addition to being functions of the antenna characteristics, A_T is also a function of β_T and θ_T, and A_R is also a function of β_R and θ_R.

A signal of strength S, in dB, is received by the receiving antenna from a target placed at any point (x,y). The target can have certain characteristics, i.e. scattering or reflecting, which are described in Section 5. The value of S depends upon:

a. The characteristics of the target,

b. The location of the target (x and y),

c. Characteristics of the antennas,

d. The aim of the antennas (β_T and β_R), and

e. The separation distance (L).

A.3 DUAL SYSTEMS

A second complete transmitting-receiving system can be added to the one already described, identical in every respect except that it is reversed, i.e. the first transmitter and second receiver occupy the point (0,0) and the first receiver and second transmitter occupy the point (L,0). The entire second system is a mirror-image of the first. The operating frequencies may be the same, or be slightly different, but the physical characteristics are otherwise identical.

A.3.1 Dual Independent Systems

The receiver uses only the signal with the larger magnitude at each target location. If the received signals, in dB, from the two systems are S_1 and S_2, respectively, then the received signal from the dual system, S, is equal to S_1 or S_2, whichever has the greater magnitude.

A.3.2 Dual Summed Systems

The receiver uses the sum of the magnitudes of the two received signals at each target location. If the received signal magnitudes, in dB, from the two systems are S_1 and S_2, respectively, then the received signal from the dual systems, S, is the sum of the respective signals, the summing performed in watts.

$$S = 10 \log_{10} \left\{ 10^{S_1/10} + 10^{S_2/10} \right\} \tag{5}$$

A.4 ANTENNA CHARACTERISTICS

A.4.1 Cosine Distribution

A cosine distribution (in dB) is a reasonable approximation to a real antenna gain distribution, without sidelobes. See Figure A-2. An equation of the form

$$\begin{aligned} A &= \frac{A_0}{2} \left[1 - \cos\phi \right] , &\quad |\phi| \le \pi \\ A &= A_0 , &\quad |\phi| > \pi \end{aligned} \tag{6}$$

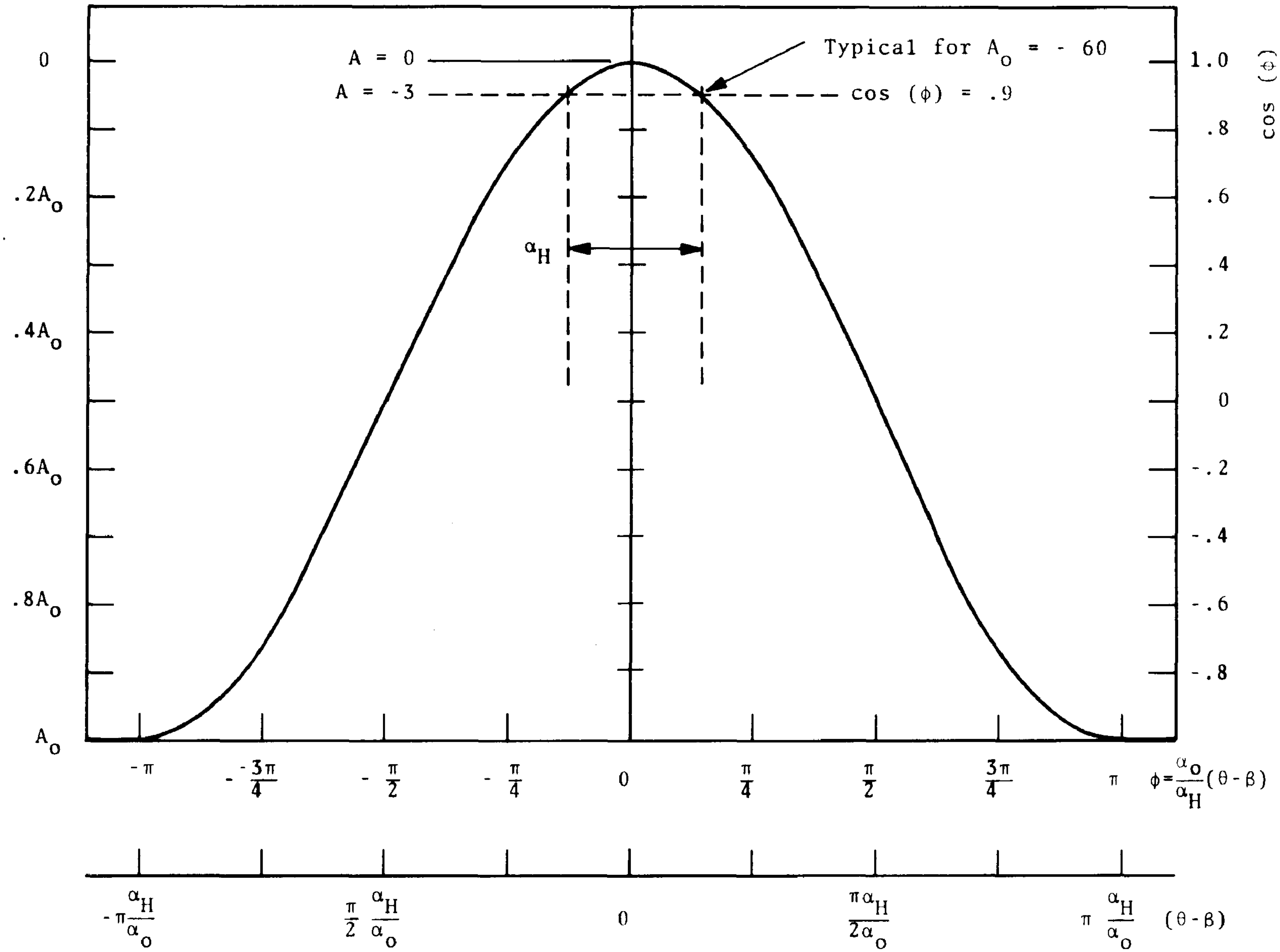

Figure A-2 Cosine Beam Distribution

can therefore be assumed, where $\emptyset$ is some angular measure, not necessary realized physically, proportional to $(\theta - \beta)$, the angle to the target measured from the beam centerline. The angle $\emptyset$, in addition, will be a function of the half-power beamwidth, α_H. Assume that

$$\emptyset \doteq \frac{\alpha_0}{\alpha_H} (\theta - \beta) \tag{7}$$

where α_0 is a constant to be defined. The half-power condition, i.e. A = -3, occurs when $(\theta - \beta) = {}^{\alpha_H}/_2$, i.e.

$$A_0 = \frac{6}{\cos(\frac{\alpha_0}{2}) - 1} \tag{8}$$

Rearranged and solved for α_0:

$$\alpha_0 = 2 \cos^{-1} \left(1 + \frac{6}{A_0} \right) \tag{9}$$

Some useful values of α_0 and A_0 are given in Table A-1.

A.4.2 Normal Distribution

A normal distribution (in dB) is another reasonable approximation to a real antenna gain distribution, without sidelobes. See Figure A-3. It has the advantage that as the off-axis angle, $\emptyset$, increases to very large values, the gain becomes asympotic

TABLE A-1 COSINE DISTRIBUTION CONSTANTS

A_0 dB	α_0 radians	α_0 degrees
-20	1.5908	91.15
-30	1.2870	73.74
-40	1.1096	63.58
-50	.9899	56.72
-60	.9021	51.68

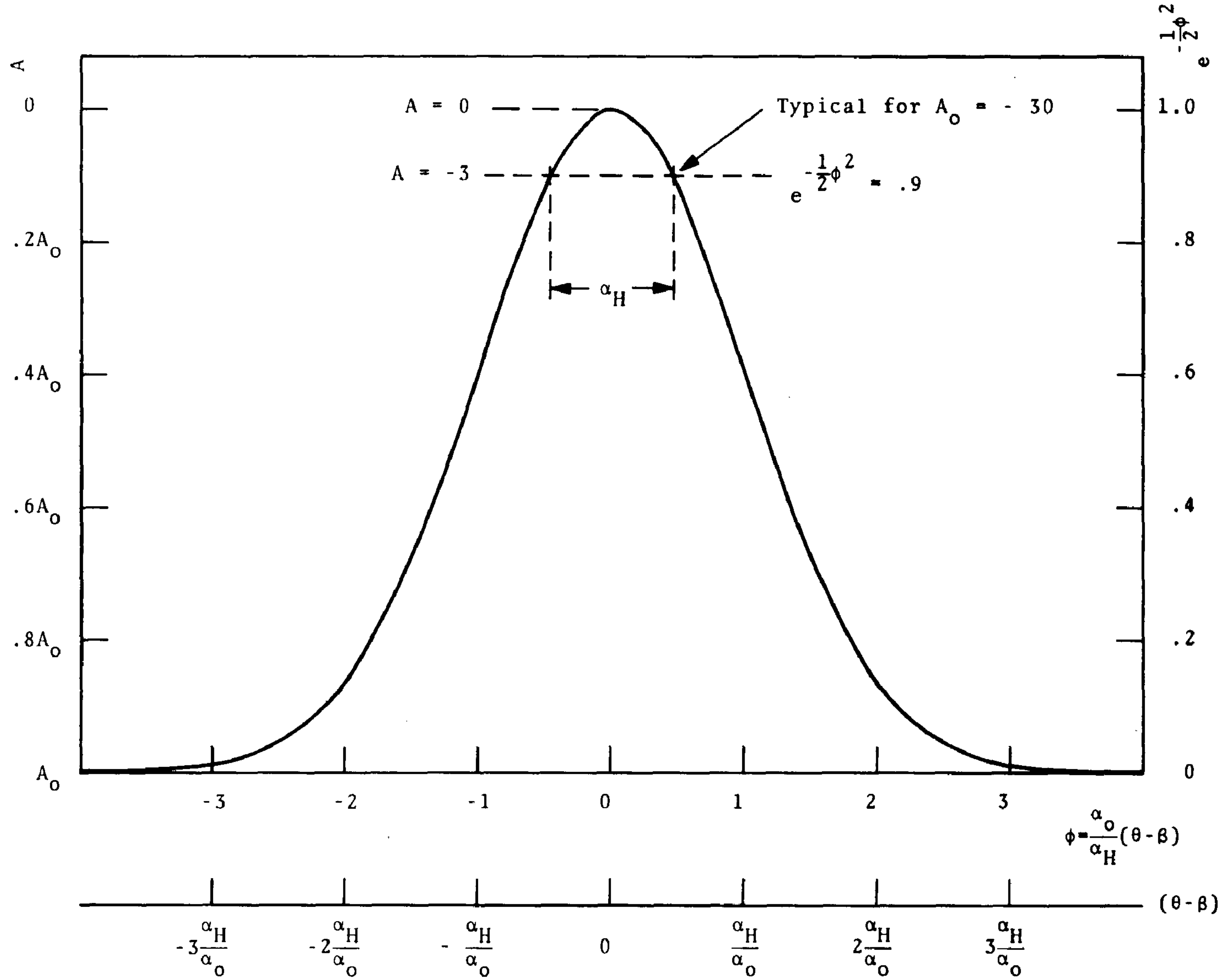

Figure A-3 Normal Beam Distribution

to its lowest value, never rising again as it does in the cosine distribution. An equation of the form

$$A = A_0 \left[e^{-\frac{1}{2}\theta^2} - 1 \right] \qquad (10)$$

can be assumed, where $\emptyset$ is some angular measure, not necessarily realized physically, proportional to $(\Theta - \beta)$, the angle to the target measured from the beam centerline. The angle $\emptyset$, in addition, will be a function of the half-power beam width, α_H. Again assume that

$$\emptyset \doteq \frac{\alpha_0}{\alpha_H} \; (\Theta - \beta) \qquad (11)$$

where α_0 is a constant to be defined. The half-power point condition, i.e. A = -3, occurs when $(\Theta - \beta) = {}^{\alpha_H}/_2$, i.e.

$$A_0 = \frac{3}{1 - e^{-\frac{1}{2}\left(\frac{\alpha_0}{2}\right)^2}} \qquad (12)$$

Rearranged and solved for α_0:

$$\alpha_0^2 = 8 \left[\log_e A_0 - \log_e (A_0 - 3)\right] \qquad (13)$$

Some useful values of α_0 and A_0 are given in Table A-2.

TABLE A-2 NORMAL DISTRIBUTION CONSTANTS

A_0 dB	α_0 radians	degrees
-20	1.140	65.33
-30	.918	52.60
-40	.790	45.25
-50	.704	40.31
-60	.641	36.70

A.5 TARGET CHARACTERISTICS

A.5.1 Scattering Target

An isotropic scattering target with $1/R^2$ loss on both transmitting and receiving paths will give a received power of

$$s = s_0 \frac{1}{R_T^{\,2}} \frac{1}{R_R^{\,2}} a_T \, a_R \tag{14}$$

This can be written as

$$\frac{s}{s_{max}} = \frac{a_T}{R_T^{\,2}} \frac{a_R}{R_R^{\,2}} \frac{s_0}{s_{max}} \tag{15}$$

Or, in dB

$$S = A_T + A_R - 10 \log_{10}(R_T^{\,2}) - 10 \log_{10} (R_R^{\,2}) - S_M \tag{16}$$

where

$$S_M = 10 \log_{10}\left(\frac{s_{max}}{s_0} \right)$$

and A_T and A_R are defined by the respective antenna distributions.

A.5.2 Reflecting Target

A pure reflecting target with $1/R^2$ loss on both transmitting and receiving paths will give a received power of

$$s = s_0 \frac{1}{(R_T + R_R)^2} \, a_T \, a_R \tag{17}$$

This can be written as

$$\frac{s}{s_{max}} = \frac{a_T \quad a_R}{(R_T + R_R)^2} \frac{s_0}{s_{max}} \qquad (18)$$

Or, in dB

$$S = A_T + A_R - 10 \log_{10} \left[(R_T + R_R)^2 \right] - S_M \qquad (19)$$

where

$$S_M = 10 \log_{10} \left(\frac{s_{max}}{s_0} \right)$$

and A_T and A_R are defined by the respective antenna distributions.

APPENDIX B

ESTIMATION OF SYSTEM EFFECTIVENESS

B.1 INTRODUCTION

In evaluating the effectiveness of dynamic passive restraint systems, one can define the following variables for accidents (collisions) of all types:

c_N, the cost of an accident when the restraint is not deployed;

c_D, the cost of an accident when the restraint is deployed;

p_D, the probability that restraint deployment will occur; and,

r_R, the cost reduction (factor) when restraints are deployed, defined as being zero for restraints of zero effectiveness (if $c_D = c_N$) and being unity for completely effective restraints (if $c_D = 0$).

The definition of the cost of an accident is complex, being in part a value judgement. Fortunately, for the purposes of this discussion it need not be defined further. However, note that it can be expressed simply in terms of number of casualties (deaths or serious injuries); economic cost is not necessarily implied. In the remainder of this treatment, it will be taken as number of lives affected per accident, but monetary cost can be obtained merely by multiplication by whatever cost factor is chosen as appropriate.

c_N, c_D, p_D, and r_R are all complicated functions of many variables. That is,

$$c_N = c_N\ (x_1,\ x_2,\ldots x_n)$$

$$c_D = c_D\ (x_1,\ x_2,\ldots x_n)$$

$$r_R = r_R\ (x_1,\ x_2,\ldots x_n)$$

The variables x_i represent as many of the parameters of automobile accidents as is feasible or meaningful to include. Examples include impact velocity, impact angle, type of accident, and vehicle crashworthiness. The last will typically be a function of the first three, and there is a degree of interdependence among all. For the problem treated here, no attempt is made at estimation of accident probability, which would complicate the task immensely and introduce many more variables. Rather,

q_A, the annual number of accidents of a type specified by a particular set of x_i, and

q_N, the corresponding annual number of casualties will be taken as data to be provided from actual accident statistics gathered prior to the use of restraints.

$$q_A = q_A\ (x_1,\ x_2,\ldots x_n)$$

$$q_N = q_N\ (x_1,\ x_2, \ldots x_n)$$

Given this foundation, one may write simple expressions for c_N and c_D:

$$c_N = \frac{q_N}{q_A} \tag{1}$$

$$c_D = (1 - r_R)\ c_N \tag{2}$$

Two quantities of primary interest can be defined;

q_R, the annual cost of all accidents of a particular type (particular set of x_i), and

q_G, the net annual cost gain in those accidents due to restraint systems.

$$q_R = q_A[p_D\ c_D + (1 - p_D)c_N] = q_R\ (x_1,\ x_2, \ldots x_n) \tag{3}$$

$$q_G = q_N - q_R = q_G\ (x_1,\ x_2, \ldots x_n) \tag{4}$$

By substituting equations 1 and 2 into equation 3 and combining it with equation 4, simpler expressions can be obtained for q_R and q_G:

$$q_G = q_N \; p_D \; r_R \tag{5}$$

$$q_R = q_N - q_G \tag{6}$$

More properly, q_N is a multidimensional density, as are q_R and q_G, and equation 5 is better written

$$q_G \; dx_1 \; dx_2 \; \ldots dx_2 = q_N \; p_D \; r_R \; dx_1 \; dx_2 \; \ldots dx_n \tag{7}$$

Total impact on auto safety, Q_G, is then obtained from integration over all accidents:

$$Q_G = \underset{\substack{\text{all} \\ \text{accidents}}}{\int_1 \int_2 \cdots \int_n} q_N \; p_D \; r_R \; dx_1 \; dx_2 \; \ldots dx_n \tag{8}$$

Since the variables x_i are in many cases neither continuous nor completely quantitative, no such integration can actually be performed. However, sufficient discrete quantization is possible to write equation 8 as a summation over volume elements in x-space.

$$Q_G = \sum_{i_1}^{m_1} \sum_{i_2}^{m_2} \cdots \sum_{i_n}^{m_n} q_{G_{i_1 i_2 \ldots i_n}} \tag{9}$$

where

$$q_{G_{i_1 i_2 \ldots i_n}} = q_{N_{i_1 i_2 \ldots i_n}} \; p_{D_{i_1 i_2 \ldots i_n}} \; r_{R_{i_1 i_2 i_n}} \tag{10}$$

and, similarly,

$$Q_R = \sum_{i_1}^{m_1} \sum_{i_2}^{m_2} \cdots \sum_{i_n}^{m_n} \left(q_{N_{i_1 i_2 \ldots i_n}} - q_{G_{i_1 i_2 \ldots i_n}} \right) \tag{11}$$

It will be in these latter forms (equations 9 and 11) that evaluation will normally be carried out; a simple computer program can do whatever processing is warranted by the data. In most cases the further assumption of product-form separability can be used:

$$q_N(x_1, x^2, \ldots x_n) = f_{q_N 1}(x_1) \quad f_{q_N 2}(x_2) \ldots f_{q_N n}(x_n) \tag{12}$$

$$p_D\ (x_1,\ x_2, \ldots x_n) = f_{p_D 1}(x_1) \quad f_{p_d 2}(x_2) \ldots f_{p_f n}(x_n) \tag{13}$$

$$r_R(x_1, x_2, \ldots x_n) = f_{r_R 1}(x_1) \quad f_{r_R 2}(x_2) \ldots f_{r_R n}(x_n) \tag{14}$$

Analysis based on this formulation is inherently limited by the data. Thus, it should be noted that great precision is neither feasible nor necessary. If a given class of accident is found to represent 4% of the total cost, with an uncertainty of 2%, this is acceptable; there would be no benefit to knowing that the true value is 3.17%. As indicated previously, it is hoped that anticipatory dynamic restraint systems can apply to a significant number of cases and represent real improvement, but it is not expected that any answer developed here will have better than 25% to 50% accuracy as to the exact magnitude of that improvement. This should be adequate for the purposes of this study.

B.2 CRASH PARAMETERS

Four primary crash parameters were selected for use in this analysis;

T, Target type,

V, Velocity of crash vehicle

A, Angle of impact, and

W, Weight of crash vehicle.

Each of the crash parameters may have any number of "values". These are not necessarily mathematical values, but may be descriptive characteristics which are serially numbered. The number of values that each parameter may have is designated n_T, n_V, n_A, or n_W, respectively. In the following analysis a lower case subscript (t, v, a, or w) will indicate the "value" of the respective parameter, a variable, while an upper case subscript (T, V, A, or W) will be a fixed subscript which relates the variable name to the respective parameter.

Each of the variables named Q, then, can be thought of as a four-dimensional array, each dimension corresponding to a crash parameter. Each element in the array is described by a lower-case subscripted name, q_A, q_N, q_R, or q_G. Four additional subscripts can then be used to signify the values, of each of the four parameters, which apply to that element.

Note that identical analyses can be made for each casualty type (fatalities, serious injuries, etc.).

The sum of all the accidents being studied, Q_A, is

$$Q_A = \sum_{t}^{n_T} \sum_{v}^{n_V} \sum_{a}^{n_A} \sum_{w}^{n_W} q_{A_{tvaw}} \tag{15}$$

the sum of all the casualties is Q_N, Q_R, or Q_G

$$Q_K = \sum_{t}^{n_T} \sum_{v}^{n_V} \sum_{a}^{n_A} \sum_{w}^{n_W} q_{K_{tvaw}} \quad , \quad K = N,R,G \tag{16}$$

B.3 SUMMATION ARRAYS

Values for q_A and q_N, from statistical tables, will be rather cumbersome to work with if they consist of all the individual elements in four-dimensional arrays. The assumption of product-form separability allows us to summarize the statistical data into four one-dimensional arrays for each variable. These are the "row" and "column" sums of array elements, and will be called here "summation arrays". The upper-case name is retained, but two additional subscripts are added, the first to name the parameter held constant, and the second to indicate that parameter's value.

$$Q_{A_{T_t}} = \sum_{v}^{n_V} \sum_{a}^{n_A} \sum_{w}^{n_W} q_{A_{tvaw}} \quad , \quad t=1,2,...n_T \qquad (17a)$$

$$Q_{A_{V_v}} = \sum_{t}^{n_T} \sum_{a}^{n_A} \sum_{w}^{n_W} \quad , \quad v=1,2,...n_V \qquad (17b)$$

$$Q_{A_{A_a}} = \sum_{t}^{n_T} \sum_{v}^{n_V} \sum_{w}^{n_W} q_{A_{tvaw}} \quad , \quad a=1,2,...n_A \qquad (17c)$$

$$Q_{A_{W_w}} = \sum_{t}^{n_T} \sum_{v}^{n_V} \sum_{a}^{n_A} q_{A_{tvaw}} \quad , \quad w=1,2,...n_W \qquad (17d)$$

$$Q_{N_{T_t}} = \sum_{v}^{n_V} \sum_{a}^{n_A} \sum_{w}^{n_W} q_{N_{tvaw}} \quad , \quad t=1,2,...n_T \qquad (18a)$$

$$Q_{N_{Vv}} = \sum_{t}^{n_T} \sum_{a}^{n_A} \sum_{w}^{n_W} q_{N_{tvaw}} \quad , \quad v-1,2,...n_V \qquad (18b)$$

$$Q_{N_{A_a}} = \sum_{t}^{n_T} \sum_{v}^{n_V} \sum_{w}^{n_W} q_{N_{tvaw}} \quad , \quad a=1,2,\ldots n_A \tag{18c}$$

$$Q_{N_{W_w}} = \sum_{t}^{n_T} \sum_{v}^{n_V} \sum_{a}^{n_A} q_{N_{tvaw}} \quad , \quad w=1,2,\ldots n_W \tag{18d}$$

As a check on data summarization, each summation array for a given variable should itself sum to the same value as the sum of the complete four-dimensional array.

$$Q_A = \sum_{t}^{n_T} Q_{A_{T_t}} = \sum_{v}^{n_V} Q_{A_{V_v}} = \sum_{a}^{n_A} Q_{A_{A_a}} = \sum_{w}^{n_W} Q_{A_{W_w}} \tag{19}$$

$$Q_N = \sum_{t}^{n_T} Q_{N_{T_t}} = \sum_{v}^{n_V} Q_{N_{V_v}} = \sum_{a}^{n_A} Q_{N_{A_a}} = \sum_{w}^{n_W} Q_{N_{W_w}} \tag{20}$$

B.4 ARRAY ELEMENTS

If the data is truly product-form separable, then, for each value of each parameter, the individual four-dimensional array elements can be calculated as a product of their respective parameter factors (see Appendix C for derivation).

$$q_{A_{tvaw}} = (f_{Q_{A_{T_t}}})\,(f_{Q_{A_{V_v}}})\,(f_{Q_{A_{A_a}}})\,(f_{Q_{A_{W_w}}}) \tag{21}$$

$$q_{N_{tvaw}} = (f_{Q_{N_{T_t}}})\ (f_{Q_{N_{V_v}}})\ (f_{Q_{N_{A_a}}})\ (f_{Q_{N_{W_w}}}) \tag{22}$$

where

$$f_{Q_{A_{J_j}}} = \frac{Q_{A_{J_j}}}{Q_A^{(3/4)}} \tag{23}$$

$$, \qquad J=T,V,A,W \quad j=1,2,\ldots n_J$$

$$f_{Q_{N_{J_j}}} = \frac{Q_{N_{J_j}}}{Q_N^{(3/4)}} \tag{24}$$

B.5 PROBABILITY AND REDUCTION FACTORS

Values for p_D and r_R are simple ratios, varying, generally, from zero to unity. (r_R for injuries may be slightly negative because of the possibility of conversion from fatality to injury.) Knowledge of the individual array element values is not required, but rather the product-form factors for each parameter value, $P_{D_{J_j}}$ and $R_{R_{J_j}}$, will be known or assumed from sensing system and restraint system characteristics. The individual array elements can, however, be calculated as

$$p_{D_{tvaw}} = (P_{D_{T_t}})\ (P_{D_{V_v}})\ (P_{D_{A_a}})\ (P_{D_{W_w}}) \tag{25}$$

$$r_{R_{tvaw}} = (R_{R_{T_t}})\ (R_{R_{V_v}})\ (R_{R_{A_a}})\ (R_{R_{W_w}}) \tag{26}$$

The results of equations 25 and 26 will be utilized in calculating the array element values of accident costs.

It should be pointed out that each of the product-form factors, $P_{D_{J_j}}$ and $R_{R_{J_j}}$ will be estimations of system deployment probability and reduction factor based on the characteristics of only one parameter value, independently of the other parameters. As there will be some interdependence of parameters on deployment probability and reduction factor in actual systems, this simplification will be useful only insofar as the results are considered to be an approximation.

B.6 COMPUTATION OF RESULTS

For any given set of values for the four parameters, an array element of Q_G and Q_R can now be calculated, using equations 5 and 6.

$$q_{G_{tvaw}} = (q_{N_{tvaw}})\ (p_{D_{tvaw}})\ (r_{R_{tvaw}}) \tag{27}$$

$$q_{R_{tvaw}} = q_{N_{tvaw}} - q_{G_{tvaw}} \tag{28}$$

A complete four-dimensional array of values is cumbersome to work with and of little value, so four summation arrays can be created for q_R and q_G, relating to the four parameters in the same way that summation arrays for q_A and q_N did. (equations 17 and 18).

$$Q_{R_{T_t}} = \sum_{v}^{n_V} \sum_{a}^{n_A} \sum_{w}^{n_W} q_{R_{tvaw}} \quad , \quad t=1,2,\ldots n_T$$

$$Q_{R_{V_v}} = \sum_{t}^{n_T} \sum_{a}^{n_A} \sum_{w}^{n_W} q_{R_{tvaw}} \quad , \quad v=1,2,\ldots n_V$$

$$Q_{R_{A_a}} = \sum_{t}^{n_T} \sum_{v}^{n_V} \sum_{w}^{n_W} q_{R_{tvaw}} \quad , \quad a=1,2,\ldots n_A \tag{29}$$

$$Q_{R_{W_w}} = \sum_{t}^{n_T} \sum_{v}^{n_V} \sum_{a}^{n_A} q_{R_{tvaw}} \quad , \quad w=1,2,\ldots n_W$$

$$Q_{G_{T_t}} = \sum_{v}^{n_V} \sum_{a}^{n_A} \sum_{w}^{n_W} q_{G_{tvaw}} \quad , \quad t=1,2,\ldots n_T$$

$$Q_{G_{V_v}} = \sum_{t}^{n_T} \sum_{a}^{n_A} \sum_{w}^{n_W} q_{G_{tvaw}} \quad , \quad v=1,2,\ldots n_V \tag{30}$$

$$Q_{G_{A_a}} = \sum_{t}^{n_T} \sum_{v}^{n_V} \sum_{w}^{n_W} q_{G_{tvaw}} \qquad , \quad a=1,2,\ldots n_A$$

$$Q_{G_{W_w}} = \sum_{t}^{n_T} \sum_{v}^{n_V} \sum_{a}^{n_A} q_{G_{tvaw}} \qquad , \quad w=1,2,\ldots n_W$$

Each summation array represented by equations (29) and (30) is a list of values of accident cost and cost gain by accident type as described by a particular characteristic (or value) of a particular parameter, either target, velocity, angle, or weight. Each element of the summation array, or each value in the list, includes all accidents occurring possessing the described characteristics irrespective of the characteristics, or values, of all of the other parameters in those accidents.

As described earlier, the sum of the elements of each summation array will be the same as the sum for the complete set of all accidents.

$$Q_R = \sum_{t}^{n_T} Q_{R_{T_t}} = \sum_{v}^{n_V} Q_{R_{V_v}} = \sum_{a}^{n_A} Q_{R_{A_a}} = \sum_{w}^{n_W} Q_{R_{W_w}} \qquad (31)$$

$$Q_G = \sum_{t}^{n_T} Q_{G_{T_t}} = \sum_{v}^{n_V} Q_{G_{V_v}} = \sum_{a}^{n_A} Q_{G_{A_a}} = \sum_{w}^{n_W} Q_{G_{W_w}} \qquad (32)$$

Equations 31 and 32 represent the predicted total annual cost of all accidents of all types (all values of all parameters), and the net annual cost gain in those accidents due to restraint systems, respectively.

B.7 HYBRID SYSTEMS

A hybrid crash sensing system consisting, typically, of an anticipatory sensor and an impact sensor and associated logic circuitry, may have different values of deployment probabilities and reduction factors associated with the different sensing sub-systems. This will require that identical analyses be performed as above for each subsystem.

The annual gains due to each subsystem (equation 32) can then be added to get the total gain for the hybrid system:

$$Q_{G(hybrid)} = Q_{G(antic)} + Q_{G(impact)} \qquad (33)$$

The resultant annual cost can then be calculated as

$$Q_{R(hybrid)} = Q_N - Q_{G(hybrid)} \qquad (34)$$

B.8 COMPUTER PROGRAM

A computer program is available* which performs the calculating task previously described. The actual accident data from a source of any size can be used. Care should be taken in selecting this source of data, however. The crash parameter distribution in it should be as close to that of the national accident data as possible, otherwise the results may be exaggerated for certain types of accidents. This implies that a large source, containing both rural and urban data, is preferred.

Input to the program is in the form of punched cards. A detailed description of the contents of the input data deck is contained in the program as comment statements. A general description is given here.

The summation arrays $Q_{A_{J_j}}$ and $Q_{N_{J_j}}$, $\begin{matrix} J=T,V,A,W \\ j=1,2,\ldots n_J \end{matrix}$,

for accidents (accident vehicles) and casualties, respectively, are used as the base data upon which the program operates. The individual elements of the summation arrays need not be computed beforehand, as the program will accept data cards with subtotals for each element, and keep running totals as new cards are read.

The names, or descriptions, of all the crash parameter values are also read from cards as input, allowing complete flexibility as to their choice for a particular source (e.g. one source may separately identify bicycles and pedestrians as targets, while another may combine them as one category of target). Up to 14 values are allowed for each of the four crash parameters.

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* Written in Fortran IV and compatible with TSC's IBM 7094 computer.

The product-form factors of deployment probabilities and reduction factors,

$$P_{D_{J_j}} \text{ and } R_{R_{J_j}} \quad , \quad \begin{array}{l} J=T,V,A,W \\ j=1,2,\ldots n_J \end{array} \quad ,$$

respectively, in percent, are input by means of a set of cards in the data deck. The values are keyed to the crash parameter values defined for the source deck by their positions on the cards and by various indexes contained on the cards.

The results may be scaled to the size of the national accident data by including the national accident totals on a data card. That card, if it contains blanks or ones, will surpress the scaling and the results will be of the same size as the source.

Most of the names of mathematical quantities in this analysis are retained in the program, except that some letter subscripts are made part of the variable name and, in some cases, the letter M or N is added as the first letter of a name to make it an integer quantity.

Output from the program is four pages of tables, one page for each crash parameter. The input values of deployment probability and reduction factors are listed, along with the name or description, for each crash parameter value on the top half-page. Below is the (scaled) summation arrays, listed by crash parameter value of accident vehicles, $Q_{A_{J_j}}$ and (for both fatalities and serious injuries) casualties without the system, $Q_{N_{J_j}}$, with the system, $Q_{R_{J_j}}$, and the casualties saved, $Q_{G_{J_j}}$. Each page contains all the j for each J, a different page is used for each J.

When a hybrid sensing system is being analysed, eight more pages are output, the second four a repeat of the first four except that the second subsystem is operating. The final four pages, then, combine the subsystems and list the results for the hybrid system.

APPENDIX C

PRODUCT-FORM SEPARABILITY

The expressions for the parameter factors (equations 23 and 24 of Appendix B) require some further explanation. In general, for an N-dimensional, product-form separable, array of elements, a, it is desired to find the factors, k;

$$a_{i_1 i_2 i_3 \ldots i_N} = (k_{1i_1})\ (k_{2i_2})\ (\ldots)\ (k_{Ni_N}) \qquad (1)$$

as functions of the sum of all elements, A;

$$A = \sum_{i_1}^{n_1} \sum_{i_2}^{n_2} \sum_{i_3}^{n_3} \cdots \sum_{i_N}^{n_N} a_{i_1 i_2 i_3 \ldots i_N} \qquad (2)$$

and the "row" and "Column" totals, or summation arrays, S.

$$S_{1i_1} = \sum_{i_2}^{n_2} \sum_{i_3}^{n_3} \sum_{i_4}^{n_4} \cdots \sum_{i_N}^{n_N} a_{i_1 i_2 i_3 \ldots i_N} \quad , \quad i_1 = 1, 2, 3 \ldots n_1$$

$$S_{2i_2} = \sum_{i_1}^{n_1} \sum_{i_3}^{n_3} \sum_{i_4}^{n_4} \cdots \sum_{i_N}^{n_N} a_{i_1 i_2 i_3 \ldots i_N} \quad , \quad i_2 = 1, 2, 3, \ldots n_2 \qquad (3)$$

$$\vdots$$

$$S_{Ni_N} = \sum_{i_1}^{n_1} \sum_{i_2}^{n_2} \sum_{i_3}^{n_3} \cdots \sum_{i_{(N-1)}}^{n_{(N-1)}} a_{i_1 i_2 i_3 \ldots i_N} \quad , \quad i_N = 1, 2, 3, \ldots n_N$$

It is claimed that a solution is

$$k_{ji_j} = \frac{S_{ji_j}}{A^{[(N-1)/N]}} \quad , \quad \begin{matrix} j=1,2,\ldots N \\ i_j=1,2,\ldots n_j \end{matrix} \qquad (4)$$

The simplest proof is to show that it works. Equation 3 can be rewritten

$$S_{1i_1} = \sum_{i_2}^{n_2} \sum_{i_3}^{n_3} \sum_{i_4}^{n_4} \cdots \sum_{i_N}^{n_N} (k_{1i_1})\,(k_{2i_2})\,(\ldots)\,(k_{Ni_N}) \quad ,$$

$i_1=1,2,\ldots n_1$

$$S_{2i_2} = \sum_{i_1}^{n_1} \sum_{i_3}^{n_3} \sum_{i_4}^{n_4} \cdots \sum_{i_N}^{n_N} (k_{1i_1})\,(k_{2i_2})\,(\ldots)\,(k_{Ni_N}) \quad ,$$

$i_2 = 1,2,\ldots n_2$

.

. (5)

.

$$S_{Ni_N} = \sum_{i_1}^{n_1} \sum_{i_2}^{n_2} \sum_{i_3}^{n_3} \cdots \sum_{i_{(N-1)}}^{n_{(N-1)}} (k_{1i_1})\,(k_{2i_2})\,(\ldots)\,(k_{Ni_N}) \quad ,$$

$i_N=1,2,\ldots n_N$

Equation 4 may be substituted into equation 5. The denominator, ${}_A[(N-1)/N]$ occurs as a factor of itself N times and becomes simply ${}_A(N-1)$.

$$S_{1i_1} = \sum_{i_2}^{n_2} \sum_{i_3}^{n_3} \sum_{i_4}^{n_4} \cdots \sum_{i_N}^{n_N} \frac{S_{1i_1} S_{2i_2} \cdots S_{Ni_N}}{{}_A(N-1)} ,$$

$i_1=1,2,\ldots n_1$

$$S_{2i_2} = \sum_{i_1}^{n_1} \sum_{i_3}^{n_3} \sum_{i_4}^{n_4} \cdots \sum_{i_N}^{n_N} \frac{S_{1i_1} S_{2i_2} \cdots S_{Ni_N}}{{}_A(N-1)} ,$$

$i_2=1,2,\ldots n_2$

.

. (6)

.

$$S_{Ni_N} = \sum_{i_1}^{n_1} \sum_{i_2}^{n_2} \sum_{i_3}^{n_3} \cdots \sum_{i_{(N-1)}}^{n_{(N-1)}} \frac{S_{1i_1} S_{2i_2} \cdots S_{Ni_N}}{{}_A(N-1)} ,$$

$i_N=1,2,\ldots\ldots n_N$

The denominator $A^{(N-1)}$ may be moved outside the summation symbols, as it is a constant divisor, and equations 6 may be factored.

$$S_{1i_1} = \frac{1}{A^{(N-1)}} \sum_{i_2}^{n_2} \left\{ \sum_{i_3}^{n_3} \left[\sum_{i_4}^{n_4} \left(\cdots \sum_{i_N}^{n_N} S_{1i_1} S_{Ni_N} \cdots \right) S_{4i_4} \right] S_{3i_3} \right\} S_{2i_2}$$

$$i_1 = 1, 2, \ldots n_1$$

$$S_{2i_2} = \frac{1}{A^{(N-1)}} \sum_{i_1}^{n_1} \left\{ \sum_{i_3}^{n_3} \left[\sum_{i_4}^{n_4} \left(\cdots \sum_{i_N}^{n_N} S_{2i_2} S_{Ni_N} \cdots \right) S_{4i_4} \right] S_{3i_3} \right\} S_{1i_1} ,$$

$$i_2 = 1, 2, \ldots n_2$$

$$\vdots$$

$$S_{Ni_N} = \frac{1}{A^{(N-1)}} \sum_{i_1}^{n_1} \left\{ \sum_{i_2}^{n_2} \left[\sum_{i_3}^{n_3} \left(\cdots \sum_{i_{(N-1)}}^{n_{(N-1)}} S_{Ni_N} S_{(N-1)i_{(N-1)}} \cdots \right) S_{3i_3} \right] S_{2i_2} \right\} S_{1i_1} ,$$

$$i_N = 1, 1, \ldots n_N \qquad (7)$$

However, recall (equations 19 and 20) that the summation arrays themselves individually sum to the same value,

$$A = \sum_{i_1}^{n_1} S_{1i_1} = \sum_{i_2}^{n_2} S_{2i_2} = \sum_{i_3}^{n_3} S_{3i_3} = \ldots = \sum_{i_N}^{n_N} S_{Ni_N} \qquad (8)$$

Therefore equations 7 become

$$S_{1i_1} = \frac{1}{A^{(N-1)}} \sum_{i_2}^{n_2} \left\{ \sum_{i_3}^{n_3} \left[\sum_{i_4}^{n_4} \left(\ldots \sum_{i_{(N-1)}}^{n_{(N-1)}} A\, S_{1i_1} S_{(N-1)i_{(N-1)}} \ldots \right) S_{4i_4} \right] S_{3i_3} \right\} S_{2i_2} \,, \quad i_1 = 1, 2, \ldots n_1$$

$$S_{2i_2} = \frac{1}{A^{(N-1)}} \sum_{i_1}^{n_1} \left\{ \sum_{i_3}^{n_3} \left[\sum_{i_4}^{n_4} \left(\ldots \sum_{i_{(N-1)}}^{n_{(N-1)}} A\, S_{2i_2} S_{(N-1)i_{(N-1)}} \ldots \right) S_{4i_4} \right] S_{3i_3} \right\} S_{1i_1} \,, \quad i_2 = 1, 2, \ldots n_2$$

.

.

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$$S_{Ni_N} = \frac{1}{A^{(N-1)}} \sum_{i_1}^{n_1} \left\{ \sum_{i_2}^{n_2} \left[\sum_{i_3}^{n_3} \left(\ldots \sum_{i_{(N-2)}}^{n_{(N-2)}} A\, S_{Ni_N} S_{(N-2)i_{(N-2)}} \ldots \right) S_{3i_3} \right] S_{2i_2} \right\} S_{1i_1} \,, \quad i_N = 1, 2, \ldots n_N \qquad (9)$$

Equations 9 can be further simplified by replacing each summation by A, from equation A8:

$$S_{1i_1} = \frac{1}{A^{(N-1)}} \sum_{i_2}^{n_2} \left[A^{(N-2)} \; S_{1i_1} \right] S_{2i_2} = \frac{A^{(N-1)}}{A^{(N-1)}} S_{1i_1} \; ,$$

$$i_1 = 1, 2, \ldots n_1$$

$$S_{2i_2} = \frac{1}{A^{(N-1)}} \sum_{i_1}^{n_1} \left[A^{(N-2)} \; S_{2i_2} \right] S_{1i_1} = \frac{A^{(N-1)}}{A^{(N-1)}} S_{2i_2} \; ,$$

$$i_2 = 1, 2, \ldots n_2$$

.

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$$S_{Ni_N} = \frac{1}{A^{(N-1)}} \sum_{i_1}^{n_1} \left[A^{(N-2)} \; S_{Ni_N} \right] S_{1i_1} = \frac{A^{(N-1)}}{A^{(N-1)}} \; S_{Ni_N} \; ,$$

$$i_N = 1, 2, \ldots n_N \qquad (10)$$

Equation 4 is, therefore, a satisfactory solution.

APPENDIX D
ACIR DATA

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 29-MAR-73 PAGE 1
ANTICIPATORY SUBSYSTEM ONLY RUN 23
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 1. TARGETS (OBJECTS STRUCK)

NO. DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1. ANOTHER CAR	90.00	100.00	100.00
2. TRUCK, BUS, TROLLEY, TRAIN	90.00	100.00	100.00
3. PEDESTRIAN, SMALL OBJECTS	0.00	100.00	100.00
4. BICYCLES WITH OR WITHOUT RIDER	20.00	100.00	100.00
5. LARGE ANIMALS	50.00	100.00	100.00
6. LIGHT FENCES	20.00	100.00	100.00
7. SHRUBBERY, SMALL TREES	10.00	100.00	100.00
8. POSTS, MAIL BOXES, GUARD RAILS	20.00	100.00	100.00
9. LARGE TREES, WALLS, BANKS, ETC, SIDESWIPE	0.00	100.00	100.00
10. LARGE TREES, WALLS, BANKS, ETC, NON-S.SWPE	50.00	100.00	100.00
11. BUMP, DITCH, CURB, ETC. (NON-COLLISION)	0.00	100.00	100.00

		--------FATALITIES---------			-----SERIOUS INJURIES------		
NO.	ACCIDENT VEHICLES	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	1271557	21718	13492	8225	960846	627579	333266
2.	425826	11293	7016	4277	260739	170302	90436
3.	911	0	0	0	720	720	0
4.	0	0	0	0	0	0	0
5.	4554	65	51	14	2161	1745	416
6.	5010	0	0	0	4682	4321	361
7.	17762	152	146	6	14045	13504	541
8.	162588	1756	1608	148	120286	111015	9271
9.	15740	282	282	0	10444	10444	0
10.	564731	8475	6692	1783	411997	332608	79389
11.	1822	0	0	0	1080	1080	0
TOTALS	2470700	43741	29287	14453	1787000	1273318	513687

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 29-MAR-73 PAGE 2
ANTICIPATORY SUBSYSTEM ONLY RUN 23
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 2. VELOCITY OF CRASH VEHICLE

NO. DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1. 1 TO 9 MPH AT IMPACT	0.00	100.00	90.00
2. 10 TO 19 MPH AT IMPACT	0.00	100.00	90.00
3. 20 TO 29 MPH AT IMPACT	0.00	100.00	90.00
4. 30 TO 39 MPH AT IMPACT	100.00	100.00	90.00
5. 40 TO 49 MPH AT IMPACT	100.00	100.00	80.00
6. 50 TO 59 MPH AT IMPACT	100.00	90.00	70.00
7. 60 TO 69 MPH AT IMPACT	100.00	75.00	60.00
8. 70 TO 79 MPH AT IMPACT	100.00	50.00	40.00
9. OVER 80 MPH AT IMPACT	100.00	20.00	10.00

		--------FATALITIES---------			-----SERIOUS INJURIES------		
NO.	ACCIDENT VEHICLES	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	61938	997	997	0	41056	41056	0
2.	145737	2081	2081	0	108401	108401	0
3.	229081	2016	2016	0	184750	184750	0
4.	444498	4812	2611	2201	341770	194632	147138
5.	589780	8648	4692	3956	451252	278566	172686
6.	537861	11314	6656	4658	386427	257033	129394
7.	291019	7825	5141	2684	184390	131468	52922
8.	91997	2926	2257	669	50779	41063	9716
9.	78789	3121	2835	286	38175	36349	1826
TOTALS	2470700	43740	29286	14454	1787000	1273318	513682

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 29-MAR-73 PAGE 3
ANTICIPATORY SUBSYSTEM ONLY RUN 23
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 3. ANGLE OF IMPACT

NO.	DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1.	9 OCLOCK (-90 DEG) FROM STRAIGHT AHEAD	0.00	0.00	0.00
2.	10 OCLOCK (-60 DEG) FROM STRAIGHT AHEAD	10.00	10.00	10.00
3.	11 OCLOCK (-30 DEG) FROM STRAIGHT AHEAD	75.00	80.00	70.00
4.	12 OCLOCK (0 DEG) FROM STRAIGHT AHEAD	100.00	100.00	100.00
5.	1 OCLOCK (30 DEG) FROM STRAIGHT AHEAD	75.00	80.00	70.00
6.	2 OCLOCK (60 DEG) FROM STRAIGHT AHEAD	10.00	10.00	10.00
7.	3 OCLOCK (90 DEG) FROM STRAIGHT AHEAD	0.00	0.00	0.00

		--------FATALITIES---------			-----SERIOUS INJURIES------		
NO.	ACCIDENT VEHICLES	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	125658	2926	2926	0	83912	83912	0
2.	109303	2709	2695	14	74188	73877	311
3.	327453	5614	3845	1769	250295	195144	55151
4.	1354445	21545	10232	11313	986775	572622	414152
5.	260961	4270	2925	1345	198436	154712	43724
6.	115679	2233	2221	12	81751	81408	343
7.	177162	4443	4443	0	111642	111642	0
TOTALS	2470700	43740	29287	14453	1786999	1273317	513681

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 29-MAR-73 PAGE 4
ANTICIPATORY SUBSYSTEM ONLY RUN 23
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 4. WEIGHT OF CRASH VEHICLE

NO.	DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1.	LESS THAN 2000 POUNDS	100.00	50.00	50.00
2.	2001 TO 3000 POUNDS	100.00	75.00	75.00
3.	3001 TO 4000 POUNDS	100.00	100.00	100.00
4.	4001 TO 5500 POUNDS	100.00	100.00	100.00

		--------FATALITIES---------			-----SERIOUS INJURIES------		
NO.	ACCIDENT VEHICLES	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	95540	2037	1673	364	61944	52436	9508
2.	467725	8930	6539	2391	330966	254763	76202
3.	1626335	28372	18245	10128	1180169	817867	362299
4.	280999	4400	2829	1571	213921	148249	65672
TOTALS	2470700	43739	29286	14454	1787000	1273315	513681

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 29-MAR-73 PAGE 5
IMPACT SUBSYSTEM ONLY RUN 23
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 1. TARGETS (OBJECTS STRUCK)

NO. DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1. ANOTHER CAR	100.00	100.00	100.00
2. TRUCK, BUS, TROLLEY, TRAIN	100.00	100.00	100.00
3. PEDESTRIAN, SMALL OBJECTS	0.00	100.00	100.00
4. BICYCLES WITH OR WITHOUT RIDER	0.00	100.00	100.00
5. LARGE ANIMALS	25.00	100.00	100.00
6. LIGHT FENCES	0.00	100.00	100.00
7. SHRUBBERY, SMALL TREES	20.00	100.00	100.00
8. POSTS, MAIL BOXES, GUARD RAILS	20.00	100.00	100.00
9. LARGE TREES, WALLS, BANKS, ETC, SIDESWIPE	10.00	100.00	100.00
10. LARGE TREES, WALLS, BANKS, ETC, NON-S.SWPE	100.00	100.00	100.00
11. SUMP, DITCH, CURB, ETC. (NON-COLLISION)	25.00	100.00	100.00

NO.	ACCIDENT VEHICLES	FATALITIES WITHOUT SYSTEM	FATALITIES WITH SYSTEM	FATALITIES REDUCTION	SERIOUS INJURIES WITHOUT SYSTEM	SERIOUS INJURIES WITH SYSTEM	SERIOUS INJURIES REDUCTION
1.	1271557	21718	18630	3087	960846	725472	235373
2.	425826	11293	9687	1605	260739	196867	63872
3.	911	0	0	0	720	720	0
4.	0	0	0	0	0	0	0
5.	4554	65	63	2	2161	2029	132
6.	5010	0	0	0	4682	4682	0
7.	17762	152	148	4	14045	13357	688
8.	162588	1756	1706	50	120286	114393	5893
9.	15949	282	278	4	10444	10188	256
10.	564731	8475	7270	1205	411997	311072	100925
11.	1822	0	0	0	1080	1014	66
TOTALS	2470700	43741	37782	5957	1787000	1379794	407205

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 29-MAR-73 PAGE 6
IMPACT SUBSYSTEM ONLY RUN 23
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 2. VELOCITY OF CRASH VEHICLE

NO. DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1. 1 TO 9 MPH AT IMPACT	0.00	100.00	90.00
2. 10 TO 19 MPH AT IMPACT	50.00	100.00	90.00
3. 20 TO 29 MPH AT IMPACT	100.00	100.00	90.00
4. 30 TO 39 MPH AT IMPACT	80.00	80.00	80.00
5. 40 TO 49 MPH AT IMPACT	60.00	50.00	50.00
6. 50 TO 59 MPH AT IMPACT	40.00	20.00	20.00
7. 60 TO 69 MPH AT IMPACT	0.00	0.00	0.00
8. 70 TO 79 MPH AT IMPACT	0.00	0.00	0.00
9. OVER 80 MPH AT IMPACT	0.00	0.00	0.00

NO.	ACCIDENT VEHICLES	FATALITIES WITHOUT SYSTEM	FATALITIES WITH SYSTEM	FATALITIES REDUCTION	SERIOUS INJURIES WITHOUT SYSTEM	SERIOUS INJURIES WITH SYSTEM	SERIOUS INJURIES REDUCTION
1.	61938	997	997	0	41056	41056	0
2.	145737	2081	1438	643	108401	75299	33102
3.	229081	2016	770	1246	184750	71918	112832
4.	444498	4812	2908	1904	341770	193340	148429
5.	589780	8648	7044	1604	451252	359387	91864
6.	537861	11314	10754	560	386427	365449	20978
7.	291019	7825	7825	0	184390	184390	0
8.	91997	2926	2926	0	50779	50779	0
9.	78789	3121	3121	0	38175	38175	0
TOTALS	2470700	43740	37783	5957	1787000	1379793	407205

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 29-MAR-73 PAGE 7
IMPACT SUBSYSTEM ONLY RUN 23
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 3. ANGLE OF IMPACT

NO. DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1. 9 OCLOCK (-90 DEG) FROM STRAIGHT AHEAD	0.00	0.00	0.00
2. 10 OCLOCK (-60 DEG) FROM STRAIGHT AHEAD	10.00	10.00	10.00
3. 11 OCLOCK (-30 DEG) FROM STRAIGHT AHEAD	90.00	100.00	100.00
4. 12 OCLOCK (0 DEG) FROM STRAIGHT AHEAD	100.00	100.00	100.00
5. 1 OCLOCK (30 DEG) FROM STRAIGHT AHEAD	90.00	100.00	100.00
6. 2 OCLOCK (60 DEG) FROM STRAIGHT AHEAD	10.00	10.00	10.00
7. 3 OCLOCK (90 DEG) FROM STRAIGHT AHEAD	0.00	0.00	0.00

		--------FATALITIES---------			-----SERIOUS INJURIES------		
NO.	ACCIDENT VEHICLES	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	125698	2926	2926	0	83912	83912	0
2.	109303	2709	2704	5	74188	73971	217
3.	327453	5614	4627	987	250295	184406	65888
4.	1354445	21545	17335	4210	986775	698150	288624
5.	260961	4270	3519	751	198436	146199	52237
6.	115679	2233	2229	4	81751	81512	239
7.	177162	4443	4443	0	111642	111642	0
TOTALS	2470700	43740	37783	5957	1786999	1379792	407205

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 29-MAR-73 PAGE 8
IMPACT SUBSYSTEM ONLY RUN 23
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 4. WEIGHT OF CRASH VEHICLE

NO. DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1. LESS THAN 2000 POUNDS	100.00	50.00	50.00
2. 2001 TO 3000 POUNDS	100.00	75.00	75.00
3. 3001 TO 4000 POUNDS	100.00	100.00	100.00
4. 4001 TO 5500 POUNDS	100.00	100.00	100.00

		--------FATALITIES---------			-----SERIOUS INJURIES------		
NO.	ACCIDENT VEHICLES	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	95640	2037	1887	150	61944	54407	7537
2.	467725	8930	7945	985	330966	270558	60407
3.	1626335	28372	24198	4175	1180169	892964	287202
4.	280999	4400	3753	647	213921	161861	52059
TOTALS	2470700	43739	37783	5957	1787000	1379790	407205

TABLE 1. TARGETS (OBJECTS STRUCK)

NO. DESCRIPTION	DEPLOYMENT PROBABILITY		REDUCTION FACTORS FATALITIES		INJURIES	
1. ANOTHER CAR	90.	100.	100.	100.	100.	100.
2. TRUCK, BUS, TROLLEY, TRAIN	90.	100.	100.	100.	100.	100.
3. PEDESTRIAN, SMALL OBJECTS	0.	0.	100.	100.	100.	100.
4. BICYCLES WITH OR WITHOUT RIDER	20.	0.	100.	100.	100.	100.
5. LARGE ANIMALS	50.	25.	100.	100.	100.	100.
6. LIGHT FENCES	20.	0.	100.	100.	100.	100.
7. SHRUBBERY, SMALL TREES	10.	20.	100.	100.	100.	100.
8. POSTS, MAIL BOXES, GUARD RAILS	20.	20.	100.	100.	100.	100.
9. LARGE TREES, WALLS, BANKS, ETC, SIDESWIPE	0.	10.	100.	100.	100.	100.
10. LARGE TREES, WALLS, BANKS, ETC, NON-S.SWPE	50.	100.	100.	100.	100.	100.
11. BUMP, DITCH, CURB, ETC. (NON-COLLISION)	0.	25.	100.	100.	100.	100.

NO.	ACCIDENT VEHICLES	--------FATALITIES--------- WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	-----SERIOUS INJURIES------ WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	1271557	21718	10406	11312	960846	392207	568639
2.	425826	11293	5411	5882	260739	106431	154308
3.	911	0	0	0	720	720	0
4.	0	0	0	0	0	0	0
5.	4554	65	49	16	2161	1613	548
6.	5019	0	0	0	4682	4321	361
7.	17762	152	142	10	14045	12816	1229
8.	162588	1756	1558	198	120286	105122	15164
9.	15960	282	278	4	10444	10188	256
10.	564731	8475	5487	2988	411997	231683	180314
11.	1822	0	0	0	1080	1014	66
TOTALS	2470700	43741	23331	20410	1787000	866115	920885

TABLE 2. VELOCITY OF CRASH VEHICLE

NO. DESCRIPTION	DEPLOYMENT PROBABILITY		REDUCTION FACTORS FATALITIES		INJURIES	
1. 1 TO 9 MPH AT IMPACT	0.	0.	100.	100.	90.	90.
2. 10 TO 19 MPH AT IMPACT	0.	50.	100.	100.	90.	90.
3. 20 TO 29 MPH AT IMPACT	0.	100.	100.	100.	90.	90.
4. 30 TO 39 MPH AT IMPACT	100.	80.	100.	80.	90.	80.
5. 40 TO 49 MPH AT IMPACT	100.	60.	100.	50.	80.	50.
6. 50 TO 59 MPH AT IMPACT	100.	40.	90.	20.	70.	20.
7. 60 TO 69 MPH AT IMPACT	100.	0.	75.	0.	60.	0.
8. 70 TO 79 MPH AT IMPACT	100.	0.	50.	0.	40.	0.
9. OVER 80 MPH AT IMPACT	100.	0.	20.	0.	10.	0.

NO.	ACCIDENT VEHICLES	--------FATALITIES--------- WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	-----SERIOUS INJURIES------ WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	61938	997	997	0	41056	41056	0
2.	145737	2081	1438	643	108401	75299	33102
3.	229081	2016	770	1246	184750	71918	112832
4.	444498	4812	707	4105	341770	46203	295567
5.	589780	8648	3088	5560	451252	186702	264550
6.	537861	11314	6096	5218	386427	236055	150372
7.	291019	7825	5141	2684	184390	131468	52922
8.	91997	2926	2257	669	50779	41063	9716
9.	78789	3121	2835	286	38175	36349	1826
TOTALS	2470700	43740	23329	20411	1787000	866113	920887

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 29-MAR-73 PAGE 11
HYBRID SYSTEM - ANTICIPATORY PLUS IMPACT SENSING RUN 23
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 3. ANGLE OF IMPACT

NO.	DESCRIPTION	DEPLOYMENT PROBABILITY		REDUCTION FACTORS FATALITIES		INJURIES	
1.	9 OCLOCK (-90 DEG) FROM STRAIGHT AHEAD	0.	0.	0.	0.	0.	0.
2.	10 OCLOCK (-60 DEG) FROM STRAIGHT AHEAD	10.	10.	10.	10.	10.	10.
3.	11 OCLOCK (-30 DEG) FROM STRAIGHT AHEAD	75.	90.	80.	100.	70.	100.
4.	12 OCLOCK (0 DEG) FROM STRAIGHT AHEAD	100.	100.	100.	100.	100.	100.
5.	1 OCLOCK (30 DEG) FROM STRAIGHT AHEAD	75.	90.	80.	100.	70.	100.
6.	2 OCLOCK (60 DEG) FROM STRAIGHT AHEAD	10.	10.	10.	10.	10.	10.
7.	3 OCLOCK (90 DEG) FROM STRAIGHT AHEAD	0.	0.	0.	0.	0.	0.

NO.	ACCIDENT VEHICLES	FATALITIES WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	SERIOUS INJURIES WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	125698	2926	2926	0	83912	83912	0
2.	109303	2709	2690	19	74188	73660	528
3.	327453	5614	2858	2756	250295	129256	121039
4.	1354445	21545	6022	15523	986775	283999	702776
5.	260961	4270	2174	2096	198436	102475	95961
6.	115679	2233	2217	16	81751	81169	582
7.	177162	4443	4443	0	111642	111642	0
TOTALS	2470700	43740	23330	20410	1786999	866113	920886

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 29-MAR-73 PAGE 12
HYBRID SYSTEM - ANTICIPATORY PLUS IMPACT SENSING RUN 23
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 4. WEIGHT OF CRASH VEHICLE

NO.	DESCRIPTION	DEPLOYMENT PROBABILITY		REDUCTION FACTORS FATALITIES		INJURIES	
1.	LESS THAN 2000 POUNDS	100.	100.	50.	50.	50.	50.
2.	2001 TO 3000 POUNDS	100.	100.	75.	75.	75.	75.
3.	3001 TO 4000 POUNDS	100.	100.	100.	100.	100.	100.
4.	4001 TO 5500 POUNDS	100.	100.	100.	100.	100.	100.

NO.	ACCIDENT VEHICLES	FATALITIES WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	SERIOUS INJURIES WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	95640	2037	1523	514	61944	44899	17045
2.	467725	8930	5554	3376	330966	194357	136609
3.	1626335	28372	14069	14303	1180169	530668	649501
4.	280999	4400	2182	2218	213921	96190	117731
TOTALS	2470700	43739	23328	20411	1787000	866114	920886

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 30-MAR-73 PAGE 1
ANTICIPATORY SUBSYSTEM ONLY RUN 24
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 1. TARGETS (OBJECTS STRUCK)

NO. DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1. ANOTHER CAR	70.00	100.00	100.00
2. TRUCK, BUS, TROLLEY, TRAIN	90.00	100.00	100.00
3. PEDESTRIAN, SMALL OBJECTS	0.00	100.00	100.00
4. BICYCLES WITH OR WITHOUT RIDER	0.00	100.00	100.00
5. LARGE ANIMALS	25.00	100.00	100.00
6. LIGHT FENCES	0.00	100.00	100.00
7. SHRUBBERY, SMALL TREES	0.00	100.00	100.00
8. POSTS, MAIL BOXES, GUARD RAILS	5.00	100.00	100.00
9. LARGE TREES, WALLS, BANKS, ETC, SIDESWIPE	0.00	100.00	100.00
10. LARGE TREES, WALLS, BANKS, ETC, NON-S.SWPE	20.00	100.00	100.00
11. BUMP, DITCH, CURB, ETC. (NON-COLLISION)	0.00	100.00	100.00

NO.	ACCIDENT VEHICLES	FATALITIES WITHOUT SYSTEM	FATALITIES WITH SYSTEM	FATALITIES REDUCTION	SERIOUS INJURIES WITHOUT SYSTEM	SERIOUS INJURIES WITH SYSTEM	SERIOUS INJURIES REDUCTION
1.	1271557	21718	18404	3314	960846	802192	158653
2.	425826	11293	9077	2216	260739	205385	55353
3.	911	0	0	0	720	720	0
4.	0	0	0	0	0	0	0
5.	4554	65	61	4	2161	2034	127
6.	5010	0	0	0	4682	4682	0
7.	17762	152	152	0	14045	14045	0
8.	162588	1756	1737	19	120286	118867	1419
9.	15940	282	282	0	10444	10444	0
10.	564731	9475	8105	369	411997	392560	19437
11.	1822	0	0	0	1080	1080	0
TOTALS	2470700	43741	37818	5922	1787000	1552009	234989

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 30-MAR-73 PAGE 2
ANTICIPATORY SUBSYSTEM ONLY RUN 24
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 2. VELOCITY OF CRASH VEHICLE

NO. DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1. 1 TO 9 MPH AT IMPACT	0.00	100.00	60.00
2. 10 TO 19 MPH AT IMPACT	0.00	100.00	60.00
3. 20 TO 29 MPH AT IMPACT	0.00	100.00	60.00
4. 30 TO 39 MPH AT IMPACT	100.00	75.00	75.00
5. 40 TO 49 MPH AT IMPACT	100.00	75.00	65.00
6. 50 TO 59 MPH AT IMPACT	100.00	60.00	50.00
7. 60 TO 69 MPH AT IMPACT	100.00	40.00	35.00
8. 70 TO 79 MPH AT IMPACT	100.00	20.00	20.00
9. OVER 80 MPH AT IMPACT	100.00	0.00	5.00

NO.	ACCIDENT VEHICLES	FATALITIES WITHOUT SYSTEM	FATALITIES WITH SYSTEM	FATALITIES REDUCTION	SERIOUS INJURIES WITHOUT SYSTEM	SERIOUS INJURIES WITH SYSTEM	SERIOUS INJURIES REDUCTION
1.	61938	997	997	0	41056	41056	0
2.	145737	2081	2081	0	108401	108401	0
3.	229081	2016	2016	0	184750	184750	0
4.	444498	4812	3774	1038	341770	268264	73505
5.	585780	8648	6783	1865	451252	367140	84111
6.	537861	11314	9362	1952	336427	331020	55406
7.	291019	7825	6925	900	184390	165883	18507
8.	91997	2926	2758	168	50779	47867	2912
9.	78789	3121	3121	0	38175	37628	547
TOTALS	2470700	43740	37817	5923	1787000	1552009	234988

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 30-MAR-73 PAGE 3
ANTICIPATORY SUBSYSTEM ONLY RUN 24
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 3. ANGLE OF IMPACT

NO.	DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1.	9 OCLOCK (-90 DEG) FROM STRAIGHT AHEAD	0.00	0.00	0.00
2.	10 OCLOCK (-60 DEG) FROM STRAIGHT AHEAD	10.00	10.00	10.00
3.	11 OCLOCK (-30 DEG) FROM STRAIGHT AHEAD	75.00	80.00	70.00
4.	12 OCLOCK (0 DEG) FROM STRAIGHT AHEAD	100.00	100.00	100.00
5.	1 OCLOCK (30 DEG) FROM STRAIGHT AHEAD	75.00	80.00	70.00
6.	2 OCLOCK (60 DEG) FROM STRAIGHT AHEAD	10.00	10.00	10.00
7.	3 OCLOCK (90 DEG) FROM STRAIGHT AHEAD	0.00	0.00	0.00

NO.	ACCIDENT VEHICLES	FATALITIES WITHOUT SYSTEM	FATALITIES WITH SYSTEM	FATALITIES REDUCTION	SERIOUS INJURIES WITHOUT SYSTEM	SERIOUS INJURIES WITH SYSTEM	SERIOUS INJURIES REDUCTION
1.	125658	2926	2926	0	83912	83912	0
2.	109303	2709	2703	6	74188	74045	142
3.	327453	5614	4889	725	250295	225065	25229
4.	1354445	21545	16910	4635	986775	797316	189458
5.	260961	4270	3719	551	198436	178434	20002
6.	115675	2233	2228	5	81751	81594	157
7.	177162	4443	4443	0	111642	111642	0
TOTALS	2470700	43740	37818	5922	1786999	1552008	234988

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 30-MAR-73 PAGE 4
ANTICIPATORY SUBSYSTEM ONLY RUN 24
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 4. WEIGHT OF CRASH VEHICLE

NO.	DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1.	LESS THAN 2000 POUNDS	100.00	30.00	30.00
2.	2001 TO 3000 POUNDS	100.00	50.00	50.00
3.	3001 TO 4000 POUNDS	100.00	80.00	80.00
4.	4001 TO 5500 POUNDS	100.00	100.00	100.00

NO.	ACCIDENT VEHICLES	FATALITIES WITHOUT SYSTEM	FATALITIES WITH SYSTEM	FATALITIES REDUCTION	SERIOUS INJURIES WITHOUT SYSTEM	SERIOUS INJURIES WITH SYSTEM	SERIOUS INJURIES REDUCTION
1.	95640	2037	1925	112	61944	58690	3254
2.	467725	8930	8108	822	330966	301991	28974
3.	1626335	28372	24195	4178	1180169	1014860	165306
4.	280999	4400	3590	810	213921	176466	37455
TOTALS	2470700	43739	37818	5922	1787000	1552007	234989

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 30-MAR-73 PAGE 5
IMPACT SUBSYSTEM ONLY RUN 24
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 1. TARGETS (OBJECTS STRUCK)

NO. DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1. ANOTHER CAR	100.00	100.00	100.00
2. TRUCK, BUS, TROLLEY, TRAIN	100.00	100.00	100.00
3. PEDESTRIAN, SMALL OBJECTS	0.00	100.00	100.00
4. BICYCLES WITH OR WITHOUT RIDER	0.00	100.00	100.00
5. LARGE ANIMALS	10.00	100.00	100.00
6. LIGHT FENCES	0.00	100.00	100.00
7. SHRUBBERY, SMALL TREES	5.00	100.00	100.00
8. POSTS, MAIL BOXES, GUARD RAILS	5.00	100.00	100.00
9. LARGE TREES, WALLS, BANKS, ETC, SIDESWIPE	0.00	100.00	100.00
10. LARGE TREES, WALLS, BANKS, ETC, NON-S.SWPE	50.00	100.00	100.00
11. BUMP, DITCH, CURB, ETC. (NON-COLLISION)	10.00	100.00	100.00

		--------FATALITIES---------			-----SERIOUS INJURIES------		
NO.	ACCIDENT VEHICLES	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	1271557	21718	19791	1927	960846	830100	130745
2.	425826	11293	10291	1002	260739	225259	35479
3.	911	0	0	0	720	720	0
4.	0	0	0	0	0	0	0
5.	4554	65	64	1	2161	2132	29
6.	5010	0	0	0	4682	4682	0
7.	17762	152	151	1	14045	13949	96
8.	162588	1756	1748	8	120286	119468	818
9.	15940	282	282	0	10444	10444	0
10.	564731	8475	8099	376	411997	383966	28031
11.	1822	0	0	0	1080	1065	15

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 30-MAR-73 PAGE 6
IMPACT SUBSYSTEM ONLY RUN 24
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 2. VELOCITY OF CRASH VEHICLE

NO. DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1. 1 TO 9 MPH AT IMPACT	0.00	100.00	60.00
2. 10 TO 19 MPH AT IMPACT	50.00	100.00	60.00
3. 20 TO 29 MPH AT IMPACT	100.00	100.00	60.00
4. 30 TO 39 MPH AT IMPACT	70.00	70.00	70.00
5. 40 TO 49 MPH AT IMPACT	50.00	40.00	40.00
6. 50 TO 59 MPH AT IMPACT	25.00	15.00	15.00
7. 60 TO 69 MPH AT IMPACT	0.00	0.00	0.00
8. 70 TO 79 MPH AT IMPACT	0.00	0.00	0.00
9. OVER 80 MPH AT IMPACT	0.00	0.00	0.00

		--------FATALITIES---------			-----SERIOUS INJURIES------		
NO.	ACCIDENT VEHICLES	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	61938	997	997	0	41056	41056	0
2.	145737	2081	1625	456	108401	93125	15276
3.	229081	2016	1133	883	184750	132679	52070
4.	444493	4812	3780	1032	341770	263104	78666
5.	585780	8648	7891	757	451252	408857	42394
6.	537861	11314	11128	186	386427	379620	6807
7.	291019	7825	7825	0	184390	184390	0
8.	91997	2926	2926	0	50779	50779	0
9.	78789	3121	3121	0	38175	38175	0
TOTALS	2470700	43740	40426	3314	1787000	1591785	195213

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 30-MAR-73 PAGE 7
IMPACT SUBSYSTEM ONLY RUN 24
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR,

TABLE 3. ANGLE OF IMPACT

NO.	DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1.	9 OCLOCK (-90 DEG) FROM STRAIGHT AHEAD	0.00	0.00	0.00
2.	10 OCLOCK (-60 DEG) FROM STRAIGHT AHEAD	10.00	10.00	10.00
3.	11 OCLOCK (-30 DEG) FROM STRAIGHT AHEAD	90.00	100.00	100.00
4.	12 OCLOCK (0 DEG) FROM STRAIGHT AHEAD	100.00	100.00	100.00
5.	1 OCLOCK (30 DEG) FROM STRAIGHT AHEAD	90.00	100.00	100.00
6.	2 OCLOCK (60 DEG) FROM STRAIGHT AHEAD	10.00	10.00	10.00
7.	3 OCLOCK (90 DEG) FROM STRAIGHT AHEAD	0.00	0.00	0.00

		--------FATALITIES---------			-----SERIOUS INJURIES------		
NO.	ACCIDENT VEHICLES	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	125658	2926	2926	0	83912	83912	0
2.	109303	2709	2706	3	74188	74084	104
3.	327453	5614	5065	549	250295	218708	31587
4.	1354445	21545	19203	2342	986775	848408	138366
5.	260961	4270	3852	418	198436	173394	25042
6.	115679	2233	2231	2	81751	81636	115
7.	177162	4443	4443	0	111642	111642	0
TOTALS	2470700	43740	40426	3314	1786999	1591784	195214

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 30-MAR-73 PAGE 8
IMPACT SUBSYSTEM ONLY RUN 24
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR,

TABLE 4. WEIGHT OF CRASH VEHICLE

NO.	DESCRIPTION	DEPLOYMENT PROBABILITY	REDUCTION FACTORS FATALITIES	REDUCTION FACTORS INJURIES
1.	LESS THAN 2000 POUNDS	100.00	30.00	30.00
2.	2001 TO 3000 POUNDS	100.00	50.00	50.00
3.	3001 TO 4000 POUNDS	100.00	80.00	80.00
4.	4001 TO 5500 POUNDS	100.00	100.00	100.00

		--------FATALITIES---------			-----SERIOUS INJURIES------		
NO.	ACCIDENT VEHICLES	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	95640	2037	1974	63	61944	59241	2703
2.	467725	8930	8470	460	330966	306896	24070
3.	1626335	28372	26035	2338	1180169	1042841	137326
4.	280999	4400	3947	453	213921	182805	31115
TOTALS	2470700	43739	40426	3314	1787000	1591783	195214

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 30-MAR-73 PAGE 9
HYBRID SYSTEM - ANTICIPATORY PLUS IMPACT SENSING RUN 24
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 1. TARGETS (OBJECTS STRUCK)

NO.	DESCRIPTION	DEPLOYMENT PROBABILITY		REDUCTION FACTORS FATALITIES		INJURIES	
1.	ANOTHER CAR	70.	100.	100.	100.	100.	100.
2.	TRUCK, BUS, TROLLEY, TRAIN	90.	100.	100.	100.	100.	100.
3.	PEDESTRIAN, SMALL OBJECTS	0.	0.	100.	100.	100.	100.
4.	BICYCLES WITH OR WITHOUT RIDER	0.	0.	100.	100.	100.	100.
5.	LARGE ANIMALS	25.	10.	100.	100.	100.	100.
6.	LIGHT FENCES	0.	0.	100.	100.	100.	100.
7.	SHRUBBERY, SMALL TREES	0.	5.	100.	100.	100.	100.
8.	POSTS, MAIL BOXES, GUARD RAILS	5.	5.	100.	100.	100.	100.
9.	LARGE TREES, WALLS, BANKS, ETC, SIDESWIPE	0.	0.	100.	100.	100.	100.
10.	LARGE TREES, WALLS, BANKS, ETC, NON-S.SWPE	20.	50.	100.	100.	100.	100.
11.	BUMP, DITCH, CURB, ETC. (NON-COLLISION)	0.	10.	100.	100.	100.	100.

NO.	ACCIDENT VEHICLES	--------FATALITIES--------- WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	-----SERIOUS INJURIES------ WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	1271557	21718	16477	5241	960846	671448	289398
2.	425826	11293	8075	3218	260739	169907	90832
3.	911	0	0	0	720	720	0
4.	0	0	0	0	0	0	0
5.	4554	65	60	5	2161	2005	156
6.	5010	0	0	0	4682	4682	0
7.	17762	152	151	1	14045	13949	96
8.	162588	1756	1729	27	120286	118049	2237
9.	15940	282	282	0	10444	10444	0
10.	564731	8475	7730	745	411997	364529	47468
11.	1822	0	0	0	1080	1065	15

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 30-MAR-73 PAGE 10
HYBRID SYSTEM - ANTICIPATORY PLUS IMPACT SENSING RUN 24
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 2. VELOCITY OF CRASH VEHICLE

NO.	DESCRIPTION	DEPLOYMENT PROBABILITY		REDUCTION FACTORS FATALITIES		INJURIES	
1.	1 TO 9 MPH AT IMPACT	0.	0.	100.	100.	60.	60.
2.	10 TO 19 MPH AT IMPACT	0.	50.	100.	100.	60.	60.
3.	20 TO 29 MPH AT IMPACT	0.	100.	100.	100.	60.	60.
4.	30 TO 39 MPH AT IMPACT	100.	70.	75.	70.	75.	70.
5.	40 TO 49 MPH AT IMPACT	100.	50.	75.	40.	65.	40.
6.	50 TO 59 MPH AT IMPACT	100.	25.	60.	15.	50.	15.
7.	60 TO 69 MPH AT IMPACT	100.	0.	40.	0.	35.	0.
8.	70 TO 79 MPH AT IMPACT	100.	0.	20.	0.	20.	0.
9.	OVER 80 MPH AT IMPACT	100.	0.	0.	0.	5.	0.

NO.	ACCIDENT VEHICLES	--------FATALITIES--------- WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	-----SERIOUS INJURIES------ WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	61938	997	997	0	41056	41056	0
2.	145737	2081	1625	456	108401	93125	15276
3.	229081	2016	1133	883	184750	132680	52070
4.	444498	4812	2742	2070	341770	189599	152171
5.	585780	8648	6026	2622	451252	324747	126505
6.	537861	11314	9176	2138	386427	324214	62213
7.	291019	7825	6925	900	184390	165883	18507
8.	91997	2926	2758	168	50779	47867	2912
9.	78789	3121	3121	0	38175	37628	547
TOTALS	2470700	43740	34503	9237	1787000	1356799	430201

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 30-MAR-73 PAGE 11
HYBRID SYSTEM - ANTICIPATORY PLUS IMPACT SENSING RUN 24
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 3. ANGLE OF IMPACT

NO.	DESCRIPTION	DEPLOYMENT PROBABILITY		REDUCTION FACTORS FATALITIES		INJURIES	
1.	9 OCLOCK (-90 DEG) FROM STRAIGHT AHEAD	0.	0.	0.	0.	0.	0.
2.	10 OCLOCK (-60 DEG) FROM STRAIGHT AHEAD	10.	10.	10.	10.	10.	10.
3.	11 OCLOCK (-30 DEG) FROM STRAIGHT AHEAD	75.	90.	80.	100.	70.	100.
4.	12 OCLOCK (0 DEG) FROM STRAIGHT AHEAD	100.	100.	100.	100.	100.	100.
5.	1 OCLOCK (30 DEG) FROM STRAIGHT AHEAD	75.	90.	80.	100.	70.	100.
6.	2 OCLOCK (60 DEG) FROM STRAIGHT AHEAD	10.	10.	10.	10.	10.	10.
7.	3 OCLOCK (90 DEG) FROM STRAIGHT AHEAD	0.	0.	0.	0.	0.	0.

		--------FATALITIES---------			-----SERIOUS INJURIES------		
NO.	ACCIDENT VEHICLES	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	125658	2926	2926	0	83912	83912	0
2.	109303	2709	2700	9	74188	73942	246
3.	327453	5614	4340	1274	250295	193479	56816
4.	1354445	21545	14568	6977	986775	658951	327824
5.	260961	4270	3301	969	198436	153392	45044
6.	115679	2233	2226	7	81751	81479	272
7.	177162	4443	4443	0	111642	111642	0
TOTALS	2470700	43740	34504	9236	1786999	1356797	430202

RESTRAINT SYSTEM EFFECTIVENESS, ACIR DATA, NHTSA-ACC905 30-MAR-73 PAGE 12
HYBRID SYSTEM - ANTICIPATORY PLUS IMPACT SENSING RUN 24
SAMPLE SIZE 5425 ACCIDENT VEHICLES, ADJUSTED TO 2470700 VEHICLES/YEAR.

TABLE 4. WEIGHT OF CRASH VEHICLE

NO.	DESCRIPTION	DEPLOYMENT PROBABILITY		REDUCTION FACTORS FATALITIES		INJURIES	
1.	LESS THAN 2000 POUNDS	100.	100.	30.	30.	30.	30.
2.	2001 TO 3300 POUNDS	100.	100.	50.	50.	50.	50.
3.	3001 TO 4000 POUNDS	100.	100.	80.	80.	80.	80.
4.	4001 TO 5500 POUNDS	100.	100.	100.	100.	100.	100.

		--------FATALITIES---------			-----SERIOUS INJURIES------		
NO.	ACCIDENT VEHICLES	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION	WITHOUT SYSTEM	WITH SYSTEM	REDUCTION
1.	55640	2037	1862	175	61944	55987	5957
2.	467725	8930	7648	1282	330966	277922	53044
3.	1626335	28372	21856	6516	1180169	877537	302632
4.	280999	4400	3137	1263	213921	145351	68570
TOTALS	2470700	43739	34503	9236	1787000	1356797	430203