Anticipatory Sensors for Collision Avoidance and Crash Protection as Applied to Vehicle Safety Research

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ABSTRACT

Considerable effort has been expended in recent years to develop anticipatory crash sensors—effective means of detecting motor vehicle collisions immediately prior to occurrence. If the potential crash is sensed early enough, evasive action may be instituted to avoid the accident. If technical or dynamic considerations limit the warning time to a very short interval, benefits can still be obtained through initiation of passive restraint deployment significantly earlier than would otherwise be the case, extending the effectiveness of such systems to higher impact speeds than are now tolerable.

The latter case—restraint system deployment—is more readily defined, and is discussed here in terms of research directed toward delineation of operational requirements, optimal means of realization, and performance characteristics. Research which has been reported by a number of investigators will be described.

Collision avoidance is a more complex topic, in that no consensus yet exists as to explicit performance objectives. Research into possible operating modes and technical realizations will be discussed, with emphasis on inherent sensor requirements in each case. Topics appropriate to future research will be indicated.

INTRODUCTION

The safety of motor vehicle operation requires continual decisions based upon surveillance of highway and surroundings. The general task of discriminating between hazardous and nonhazardous conditions, and taking appropriate action, is one which—like pattern and speech recognition—human beings can accomplish with considerable success. However, incapacitation, inattention, or inadequate skill can lead to accidents, and it is natural to seek to develop automatic systems to augment or replace, insofar as possible, certain of the safety-related tasks facing an automobile driver. Crucial to this goal is realization of effective means of surveillance of vehicle surroundings and identification of hazards. This must be achieved in such a manner as to permit effective countermeasures. Detection of potential collision objects prior to actual impact is often referred to as "anticipatory sensing," and is the subject of this paper.

Research on anticipatory sensors has been directed primarily at two potential applications. The first is collision avoidance, which can merely refer to alerting the driver, or could (conceptually) include automatic steering, braking, and accelerating of the vehicle along a safe trajectory. The second topic to which pre-sensing is relevant is actuation of deployable passive restraint systems, for which a small advance warning can extend system effectiveness to relatively high impact speeds. These two application classes are quite distinct, in that one requires sensing at tens to

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hundreds of meters distance, whereas the other needs an effective range of only one to three meters. However, the potential collision objects are the same in each case, and basically similar technologies have been investigated by various researchers. Thus it is appropriate that research in both areas be described here. This paper draws heavily upon the research of other groups and individuals, both published and unreported, and is intended to provide a meaningful survey of the current state-of-the-art. However, the proprietary nature of the field limits the flow of information, and this presentation does not purport to be all-inclusive.

For the purposes of this discussion, a broad definition of "anticipatory sensor" will be assumed. That term is used here to include both the means of obtaining the necessary information—the surveillance function—and such signal processing as is required to provide necessary output actuation signals. For example, if automatic braking is envisioned, the anticipatory sensor output would directly control both the timing and degree of brake application, operating through an electromechanical interface. Separation of surveillance and information processing is an artificial distinction here, in that the nature of the processing depends upon the information gathered. This intimate relationship between basic sensing, data processing, and ultimate function implies that required overall system characteristics be sharply defined in the initial phase of investigative efforts. Since that function which is desired may not, in fact, be feasible, an iterative process is often needed to determine a research goal which is both attainable and of real value. A major aspect of anticipatory sensor research has been determination of reasonable overall objectives and selection of the technology by which they can be achieved. Thus, a significant part of this paper will deal with such topics.

GENERAL CONSTRAINTS ON ANTICIPATORY SENSORS

There are a number of constraints which must be satisfied by any anticipatory sensor if it is to be viable in general automotive use. Major requirements are listed below.

HIGH RELIABILITY

Automobiles often have a long useful life, even with relatively little special care. At the same time, a viable sensor must achieve a very low failure rate, with respect to both failure to operate when needed, and to inadvertent operation when not appropriate. Design must be fail-safe, in that the least hazardous condition occurs in the event of failure. In both categories, the reliability requirements for anticipatory sensors far exceed those normally imposed on automotive systems. Also, failure of the sensor to actuate subsystems because of inherent inability to detect the potential collision object must be uncommon, and actuation of avoidance procedures or restraint deployment must virtually never occur as a result of inadequacies of the object detection process. That is, target discrimination must be good.

OPERATING ENVIRONMENT

The automotive environment includes a wide temperature range, exposure to high levels of moisture, and much foreign matter. Vibration can be severe, and the electrical environment includes high noise levels and large voltage variations.

VANDALISM

It is possible that triggering of anticipatory sensors could be seen by vandals as an enjoyable sport. Thus, it is important that false triggering not be readily accomplished by those so inclined. Similarly, the sensor must not be easily damaged by direct malicious acts.

LOW COST

There are two basic limitations on cost. The first is that of the marketplace. The second consideration is a more rigorous overall cost/benefit evaluation in terms of true societal costs. Both approaches have generally been found to imply a restriction in the range of $50 to $250 per vehicle as sold to the consumer. OEM price must, of course, be much lower.

RESEARCH INTO POSSIBLE TECHNIQUES FOR ANTICIPATORY SENSING

There are many known or conceivable means of sensing the presence, closing rate, and nature of nearby physical objects, but most methods can be discarded immediately as far as this application is concerned. Indeed, the real burden is to demonstrate that *any* truly promising methods can be found. The basic classifications of sensors which have been considered are mechanical, proximity, and ranging. Mechanical methods include the use of probes, extendable bumpers, etc. Proximity techniques are basically static, such as capacitive, inductive, magnetic, etc. In ranging sensors, energy is radiated ahead of the automobile and the reflection (if any) is analyzed to provide information as to the range, movement, and nature of the reflecting object. The consensus of research findings with respect to these classes will now be discussed briefly, with the understanding that system details inevitably depend upon required operational characteristics.

MECHANICAL SENSORS

Mechanical sensors are inherently relevant only to short-range crash prediction. One must, in essence, advance the physical position of the sensor relative to the vehicle. An indication of the mass or immobility of such a target is necessary in order to predict the seriousness of the collision. While a mechanical sensor offers this capability, its sensitivity depends upon the capacity of the sensing system to absorb energy. A physically small sensor extended in front of the car might undergo severe decelerations even for relatively minor impacts. Alternatively, a massive structure which could better judge the seriousness of the crash would be a complex and expensive device, since substantial extension would be necessary, and it would presumably have to be retractable. Thus, this approach has not found favor.

PROXIMITY SENSORS

Inductive, capacitive, and magnetic vehicle detection systems are well-known. However, for this application it would be difficult—often impossible—to distinguish between effects of range, velocity, size, and target characteristics. Capacitive or inductive sensors would also require inconveniently large structures. Infra-red radiometric sensing is vulnerable to environment, and temperature-discrimination would be a poor means of determining the relative hazard of obstacles. Proximity techniques have generally been found insufficiently promising to warrant detailed investigation for this task.

RANGING SYSTEMS—OPTICAL

Good discrimination of target position is possible, and sharply-focused optical systems can provide determination of obstacle dimensions. The closing rate can readily be measured. However, optical sensors are vulnerable to dirty apertures and dust, fog, or snow in the air. Finally, attaining satisfactory target discrimination does not appear possible.

RANGING SYSTEMS—SONIC

For an air-medium, high-resolution system, relatively short wavelengths are required. Avoidance of creation of audible noise, as well as reduced susceptibility to environmental noise, imply frequencies above the audible range, but frequency is limited by atmospheric attenuation which can be quite large at higher frequencies. Thus, 30 to 100 kHz has been found to be the optimum for an acoustic sensor. The basic requirement for very wide bandwidth, combined with the need for a transducer "window" operable under severe weather conditions, raises both technical and economic problems. Attenuation and susceptibility to wind and noise are serious problems. Finally, target discrimination is quite poor. Thus, this approach has not been widely explored.

RANGING SYSTEMS—RADAR

Radar has been used extensively for object detection, particularly in aviation and marine applications. The frequency, transit time, amplitude, phase, direction, and polarization of a reflected radio signal all can provide information about the reflecting object and its motion relative to the radar system. For significant directivity, the antennas used must have dimensions large compared to the radio wavelength; this consideration alone dictates use of frequencies of 10 GHz and above. (Component prices tend to be a minimum at 10 GHz, rising sharply with frequency.) Range and rate can be determined accurately, but the size of the target must be inferred primarily from the magnitude of the returned signal. One can expect only limited correlation between target lethality and radar cross-section. However, motor vehicles, which are the major obstacle category, generally provide a strong reflection. In summary, microwave radar suffers less from poor target discrimination than do other methods, and has in its favor a wealth of known techniques and available components. On balance, this approach has been selected for detailed investigation by a number of investigators, and almost all reported experimental anticipatory sensors have been based upon radar technology. A discussion of such research follows.

RESEARCH INTO ANTICIPATORY SENSORS FOR CRASH PREDICTION

The relevance of presensing to crash prediction arises from the development in recent years of deployable passive restraint systems, such as airbags. The maximum impact speed at which such devices can be effective is crucially dependent upon the means by which the collision is sensed. Conventional electromechanical sensors typically do not actuate until 17 to 30 msec after the collision has begun. When one adds 20 to 30 msec additional for restraint system deployment, the total time budget required is so large as to limit overall system effectiveness severely in crashes occurring at barrier-equivalent impact speeds greater than approximately 30 MPH. However, improved vehicle structures and airbags offer the potential of survivability for velocities of 50 to 60 MPH. The key to this performance is initiation of restraint deployment sufficiently early in the crash sequence. In view of the large percentage of casualties which occur in the impact speed range from 30 to 60 MPH, such capability is highly desirable, and it is this goal which provides the motivation for development of crash prediction sensors.

Basic Requirements

Analysis has shown that crash prediction sensors need acquire and process only limited information. Since overall system operation requires only 25 to 35 msec anticipation, a sensing distance as short as one meter is adequate. For collision speeds of interest, no meaningful changes in velocity or trajectory will occur prior to impact, so it is only necessary to detect the presence of a potentially hazardous object within a small region ahead of the car, with a relative closing rate greater than the threshold velocity for which deployment is deemed necessary. The basic sensing needs, therefore, are threefold: 1) Position (occupation of a critical volume); 2) Velocity (closing rate above a specified threshold); and 3) Nature of obstacle. Each of these elements will now be considered.

POSITION DISCRIMINATION

Simple detection of the presence or absence of an obstacle immediately in front of a vehicle is relatively simple, and rather similar approaches have been reported by Toyota, GM, and TSC. In essence, a bistatic arrangement is used (physically separated receiving and transmitting antennas), with position discrimination arising from overlap of the antenna patterns. Only objects simultaneously in both beams will reflect energy from the transmitter to the receiver (see Figure 1). Both Toyota and TSC have described use of four-antenna systems to obtain a more-nearly optimum region of coverage; Figures 2a and 2b show calculated regions of sensitivity for particular 2-antenna and 4-antenna systems, respectively.

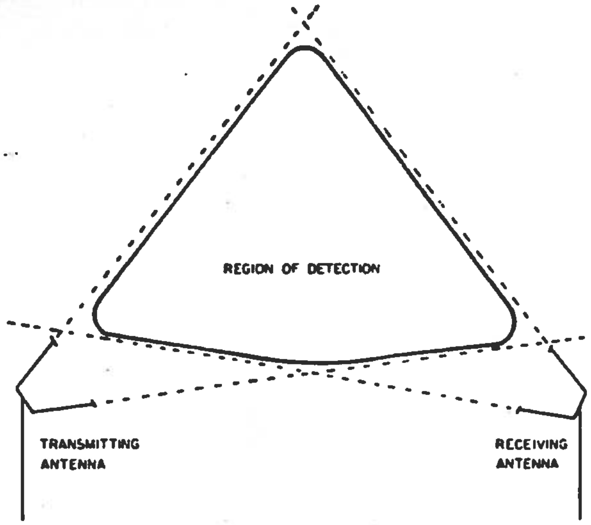


Figure 1. Basic bistatic system

VELOCITY DISCRIMINATION

This is similarly straightforward, and reported radar sensors have generally been CW doppler systems. Mixing of the received signal with a sample of the transmitted energy—a very simple process—generates an output at the difference frequency, which is proportional to the closing rate. This doppler output is at a readily utilized frequency: 31 Hz per MPH for a 10 GHz system. Thus, simple audio-frequency discrimination circuits can be used. A more sophisticated approach is possible if desired, in which actuation criteria and time, and inflation rate, are functions of closing rate.

TARGET DISCRIMINATION

This task has generally been found to be the most challenging aspect of anticipatory sensing. In principle one can derive considerable information from the amplitude, phase, frequency, transit time, direction, and polarization of a reflected microwave signal, particularly when examined over a significant time interval. However, it is not clear that even a relatively elaborate system will distinguish with sufficient precision between targets of varying lethality, and such techniques can be expensive. The most common approach has been to use reflected signal amplitude. This is a reasonable—though far from perfect—first approximation, since motor vehicles are usually good reflectors. Figure 3 shows (in conceptual form) the basic predictive crash sensor configuration typically considered.

Experimental Realizations

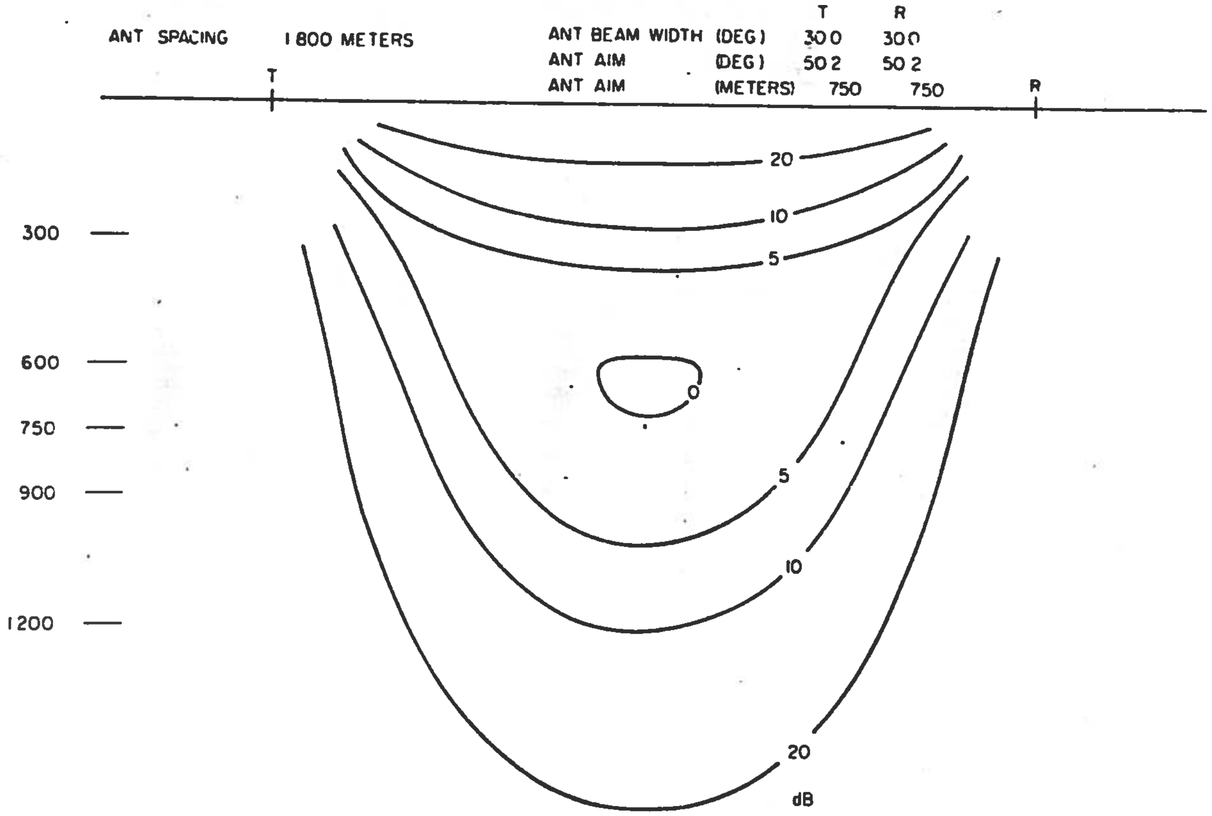
Laboratory prototype sensors have been constructed by a number of researchers (see Figure 4). Those systems which have been formally reported have been single-frequency radars, although promising work has been done by Sperry Rand and others utilizing sophisticated short-pulse systems, which, in effect, carry out simultaneous observation over a wide range of frequencies. Experimental radar sensors typically have utilized existing microwave technology. Both conventional horn antennas and newer, far more compact planar array antennas have been used. This latter type offers both cost benefits ($1 to $3 per antenna) and greater compatibility with automotive use. An example of such an antenna is shown in Figure 5. Solid state microwave oscillators, requiring only a 10 to 15 V DC power source, have in recent years become sufficiently developed and economical to be considered for consumer markets, and are highly suited to the crash sensing application. Most reported research has been based on these devices. Conventional mixer diodes ordinarily comprise the receiver, with all further circuit functions involving only low (audio) frequency elements.

Signal processing is commonly carried out either with analog/digital or purely digital circuits. Our studies indicate that the basic function can be achieved utilizing a single LSI (Large Scale Integration) chip, at a cost of several dollars (in automotive volume) and with extremely high circuit reliability.

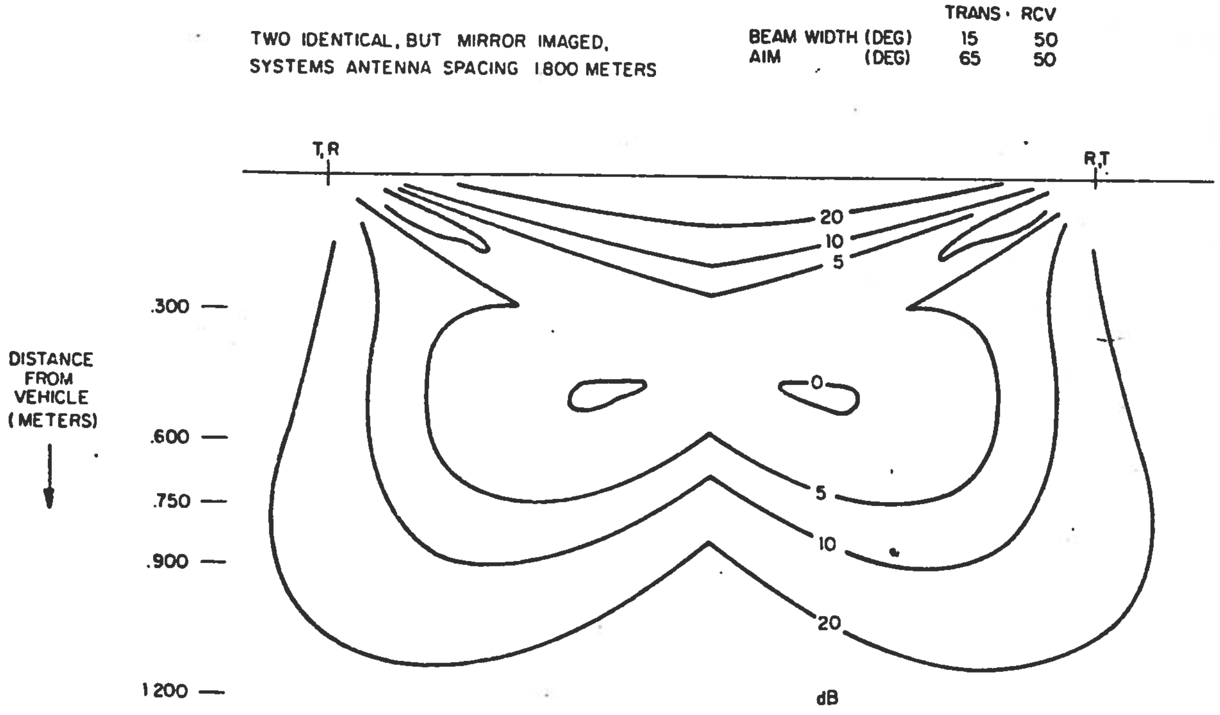
Performance Considerations

TARGET DISCRIMINATION

As indicated previously, this is the most critical and weakest aspect of radar sensors. Researchers in the field have found (not surprisingly) that radar reflections from



(a) Single antenna pair



(b) Dual antenna pair

Figure 2. Detection sensitivity patterns (calculated)

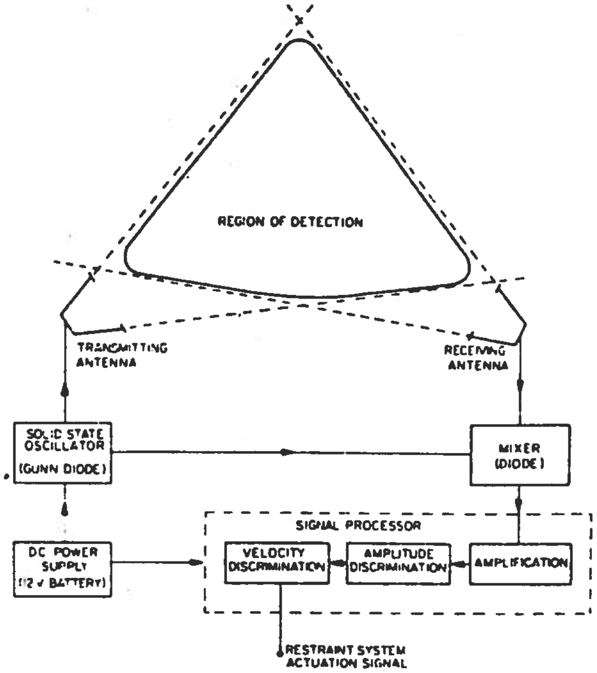


Figure 3. Basic overall crash prediction radar anticipatory sensor

hazardous objects, such as trees, may be substantially lower than returns from relatively innocuous obstacles such as roadside signposts, etc. Automobiles, which represent approximately one-half of collision objects, provide a strong reflection from most angles, and concrete walls are also "good" targets. Telephone poles are difficult to sense at a high level. Typical doppler reflections are shown in Figures 6 and 7. There appears to be no easy solution to this difficulty; radar sensors are inherently imperfect, and–if placed in service for restraint actuation–could fail to operate in some circumstances when needed. Attempts to alleviate this by easing the triggering criteria would lead to an unacceptable "false-alarm" rate. On the other hand, it should be noted that even partial success in this area can provide an effective and desirable safety system, particularly in view of the large number of fatalities occurring in the higher speed ranges for which presensing is relevant.

ENVIRONMENTAL EFFECTS

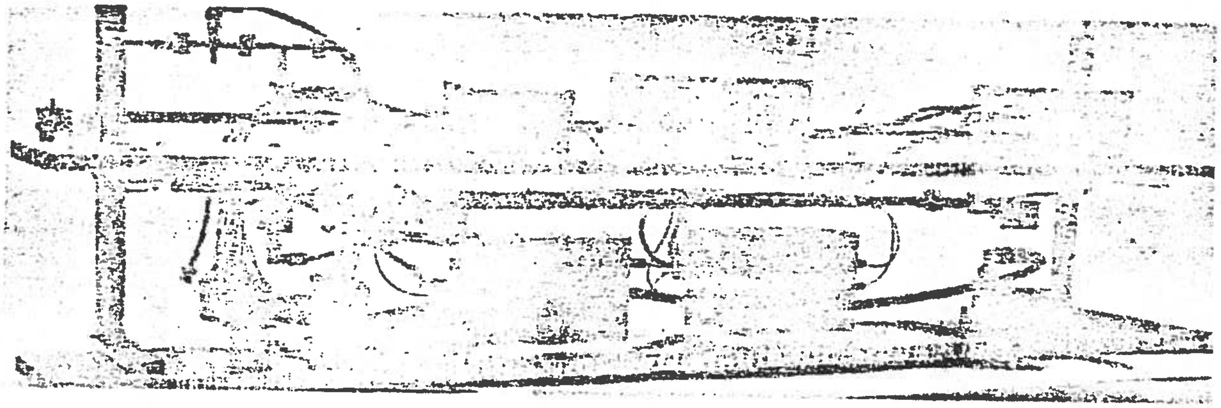
Potential difficulties associated with false activations, due to rain, splashing water, etc., have been investigated and reported by Toyota. They find some problem when low triggering thresholds are set. However, the difficulty does not seem to be severe, particularly when proper signal processing and shaping of antenna patterns are included in basic designs.

INTERVEHICLE INTERFERENCE

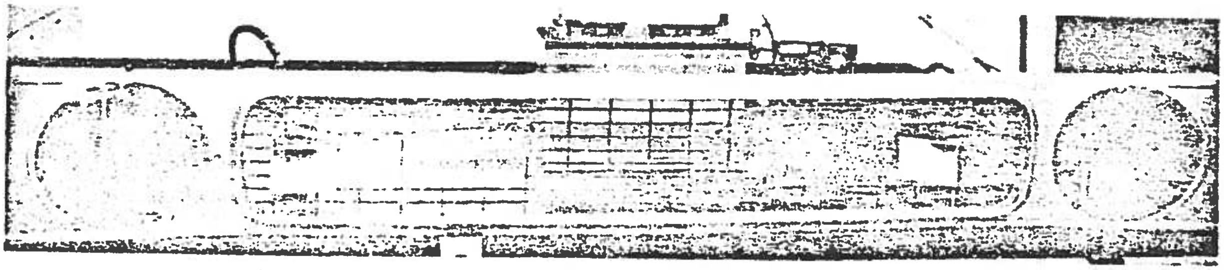
In general use, each radar receiver will often be exposed to signals transmitted by other vehicles, with the possibility of false actuation by misinterpretation of the intruding signal as a reflection. Fortunately, the antenna configuration, short required range, and high triggering threshold used in this application tend to operate strongly against this problem. Simple distribution of crash sensor radars over a wide band would be adequate, but it is desirable that only a narrow band be needed, and that such interference be made a truly negligible factor. The benefits of applying frequency modulation to the carrier have been investigated at TSC. Simple sweeping over a 25 MHz range can provide virtually complete protection if the sweep rates vary from car to car (see Figure 8). No two systems can then stay sufficiently close in frequency for a long enough time to generate a sufficient number of simulated doppler cycles to trigger the system. Alternatively, noise modulation of the carrier frequency has been shown–both analytically and experimentally–to achieve statistically complete immunity with a very narrow crash sensor frequency band (Figure 9).

RADIATION HAZARD

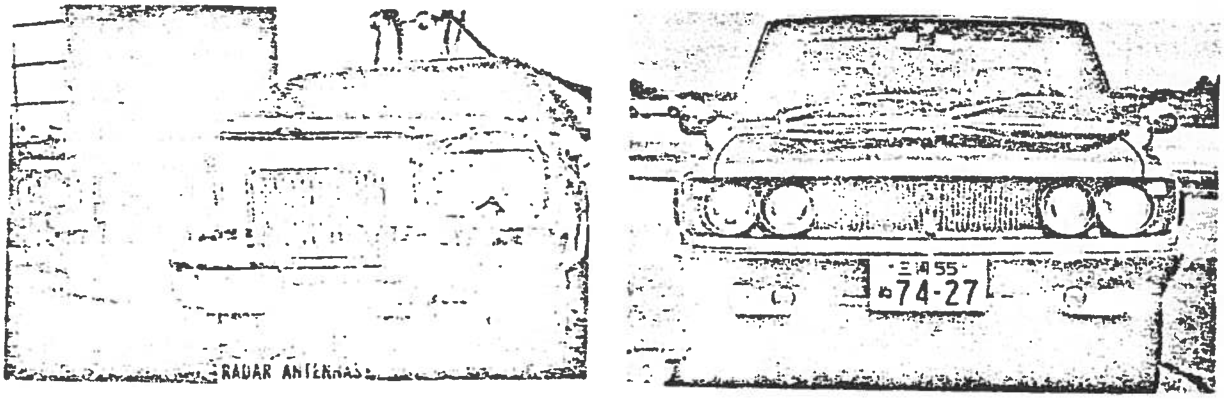
The possibility of harm to those people who are, by virtue of occupation or habit, constantly exposed to radiation from vehicles must be considered. Once again, the short-range nature of the system is helpful. Successful operation requires no more than 10 mW output, and this implies a power density at the antenna of approximately .25 mW/cm², one-quarter the generally allowed level. At a range of one meter the level is down to .002 mW/cm², one-fifth of the intensity permitted



(a) Three-frequency test set; 10, 22, and 35 GHz (TSC)

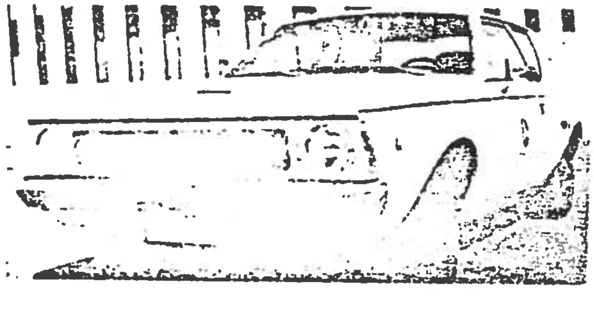


(b) Laboratory model, 10 GHz (TSC)



(c) Mounted in vehicle (GM)

(d) Mounted in vehicle (Toyota)



(e) Mounted in vehicle (TSC)

Figure 4. Prototype anticipatory sensors

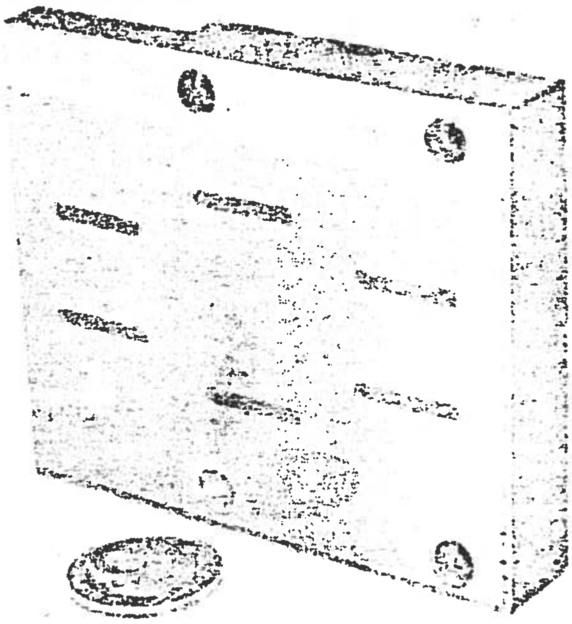
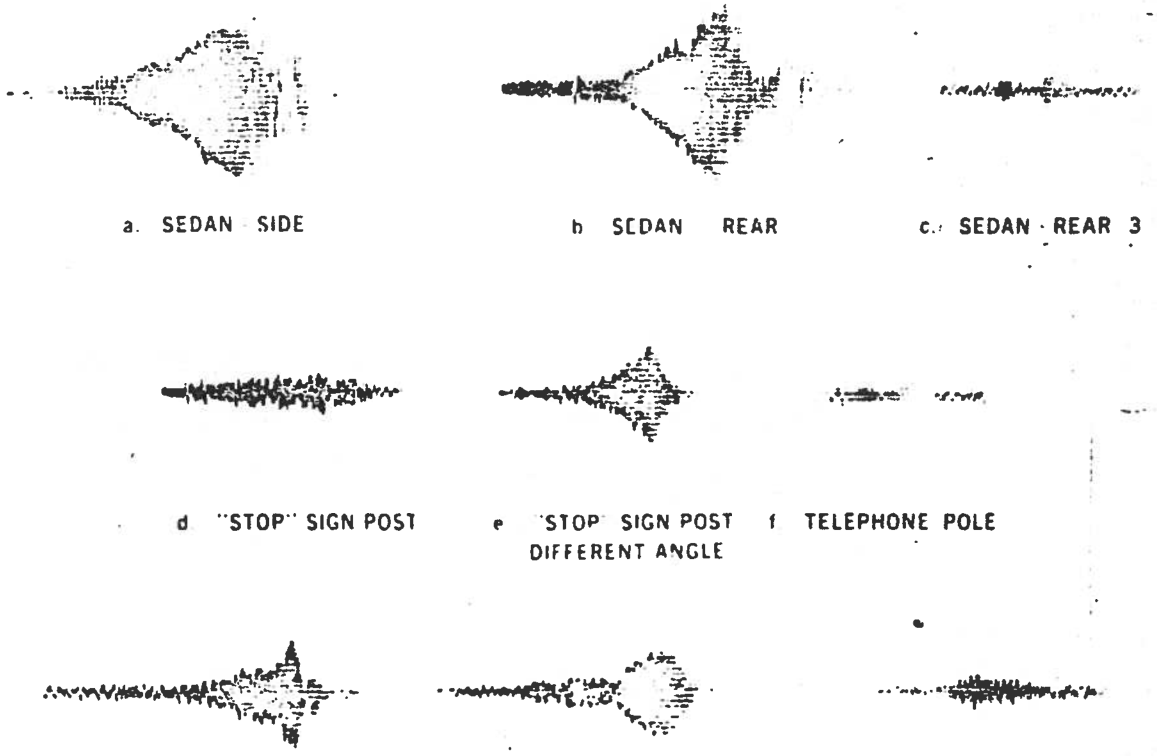


Figure 5. Waveguide-fed slot array planar antenna (center frequency 10.525 GHz; dimensions 2-1/8 × 2-5/8 × 1/2"; gain 13 dB; pattern 23° × 37° nominal; constructed by Rantec Division of Emerson Electric under TSC contract.)

for continuous exposure under the conservative standards of the USSR. If desired, power could be reduced still further and effectiveness would be unaffected.

COST

Cost has always been seen as a major challenge to crash sensor viability and has received considerable attention. Although the components involved are typically hundreds of dollars in unit purchases, automotive volume offers very dramatic reduction. TSC has undertaken specific studies concerning both the antennas and signal processing circuitry and finds a cost of approximately $3 per antenna (two required) and $4 for the basic circuit. The microwave components (oscillator and mixer diodes), in a properly integrated form, should add approximately $5. Thus, given the presence of a deployable passive restraint system in a vehicle, the OEM cost of adding anticipatory crash prediction should be approximately $15. Adding the



a. SEDAN SIDE

b SEDAN REAR

c. SEDAN · REAR 3 4

d "STOP" SIGN POST

e "STOP" SIGN POST DIFFERENT ANGLE

f TELEPHONE POLE

g STREET LIGHT POLE

h. CONCRETE WALL

i. TREE 18" DIA

Figure 6. Doppler radar signatures of various targets at 10 GHz (TSC)

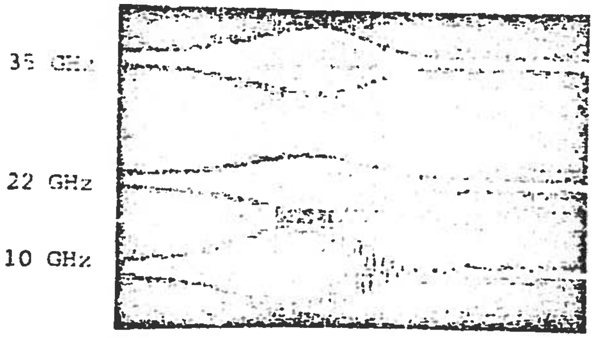
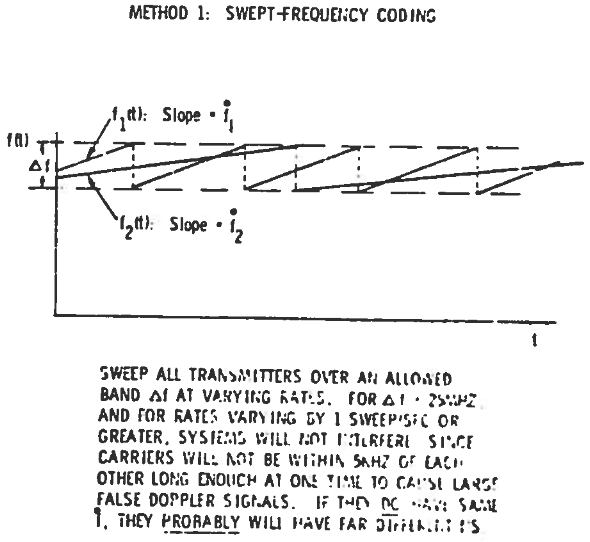


Figure 7. Comparison of doppler radar signatures of concrete post at 10, 22, and 35 GHz (TSC)

cost of installation and the tests, handling, and profit margins associated with bringing a product to the consumer will lead to a price for the final purchaser of $50 to $75. However, it is also necessary to include other life-cycle costs—inspection, maintenance, amortization, etc.—and experience suggests that these aspects typically double the total cost to users of technological systems. Thus, one obtains a final—if very approximate—estimate of total consumer cost of $100 to $150 per vehicle.

Topics for Further Research

In addition to refinement of system characteristics and determination of optical circuit realization, several areas warrant further research if anticipatory sensors are to achieve viable performance in crash prediction applications.



SWEEP ALL TRANSMITTERS OVER AN ALLOWED BAND Δf AT VARYING RATES. FOR Δf = 25MHZ AND FOR RATES VARYING BY 1 SWEEP/SEC OR GREATER, SYSTEMS WILL NOT INTERFERE SINCE CARRIERS WILL NOT BE WITHIN 5KHZ OF EACH OTHER LONG ENOUGH AT ONE TIME TO CAUSE LARGE FALSE DOPPLER SIGNALS. IF THEY DO HAVE SAME $\dot{f}$, THEY PROBABLY WILL HAVE FAR DIFFERENT f'S

Figure 8. Interference countermeasures. Linear frequency modulation

TARGET DISCRIMINATION

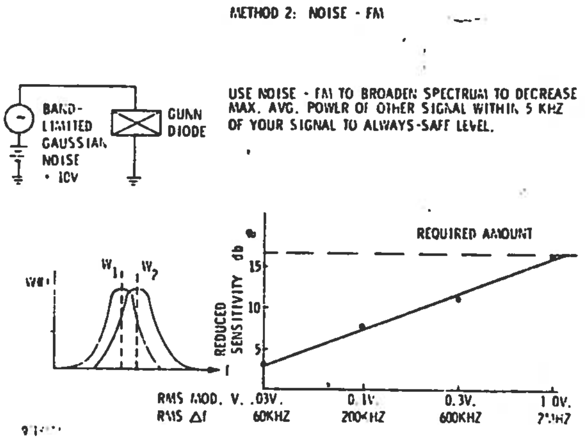
As indicated above, considerably more information can be acquired with radar than is utilized by crash sensors constructed to date. General Motors researchers have drawn attention to the potential benefits of comprehensive radar signature studies, aimed at successful discrimination between hazardous 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. This applies equally to single-frequency and short-pulse techniques.

HYBRID SYSTEMS

Utilization of sensing means additional to radar also can significantly mitigate discrimination problems. TSC has proposed addition of bumper-mounted impact switches for intermediate speeds, and GM has pointed out potential benefits of lasers for determination of target size. However, there has been no large-scale effort to explore such concepts.

OPERATION IN A REALISTIC ENVIRONMENT

Although a number of research groups have tested anticipatory sensors under normal



USE NOISE - FM TO BROADEN SPECTRUM TO DECREASE MAX. AVG. POWER OF OTHER SIGNAL WITHIN 5 KHZ OF YOUR SIGNAL TO ALWAYS-SAFE LEVEL.

Figure 9. Interference countermeasures. Noise modulation

(and abnormal) conditions, implementation of such devices would require a lengthy and full-scale test involving fleet installation with appropriate recording devices.

RESEARCH ON ANTICIPATORY SENSORS FOR COLLISION AVOIDANCE

Possible Modes of Operation

Examination of accident statistics suggests that very large costs are associated with collisions which might have been averted or moderated by timely brake application or evasive maneuvers. Development of technology which offers the possibility of electronic assistance in this task has led to increasing interest in recent years in the subject of automatic motor vehicle collision avoidance systems. However, what at first glance may seem a relatively straightforward problem is, in fact, very complex in terms of both definition and technical realization of optimal operating characteristics. Although experimental tests of various operational concepts and specific hardware are of importance, the variety of modes and characteristics possible requires careful attention to proper analysis and definition of requirements. Most of the systems which have been investigated or proposed in recent years fall somewhere within the following categories, listed in order of increasing technical complexity:

1. Driver advisory/alarm, warning of possible hazards;
2. Headway control under constrained conditions;
3. Maximum braking, in emergency situations only;
4. Completely general, full-time use, applying moderate braking whenever needed for obstacle avoidance; and
5. General collision avoidance, including steering, braking, and acceleration.

Basic System Requirements

In addition to the general constraints delineated earlier, it is particularly important that fully automatic systems be such that occasions on which a correctly operating device *causes* an accident must be extremely rare. Such events could occur, for example, through unwarranted brake applications in heavy traffic, or through prevention of evasive maneuvers. Also, the driver who is discomfited, placed in jeopardy, or merely annoyed once a week or even once a month is very likely to disable the device permanently, and a significant incidence of this could destroy overall value.

Further, it must be remembered that the typical driver compiles an impressive record. It has been estimated that the human failure rate in brake applications is less than one in 100,000. Construction of an economically feasible system which can surpass the human capability for sensing, interpreting, and acting upon information about one's surroundings is a challenging task.

Technical Requirements

As outlined above, there are many possible operating modes, each implying somewhat different technical needs. However, certain requirements are virtually inherent in accident statistics. For example, the vast number of rear-end collisions make clear the crucial importance of this class of obstacle. Therefore, any system must respond effectively in virtually all cases involving this target. Further, a very large number of urban accidents involve striking a stopped vehicle, so sensing of fixed (stationary) objects is important in most potential applications.

The general target discrimination considerations relating to crash prediction apply here, also. Basic operation of avoidance systems invariably implies some measurement of range and closing rate. Some indication of position—whether the target is actually in a vehicle's path—is necessary. More sophisticated systems or operating modes require more information concerning the trajectory of the obstacle as seen by the vehicle. A range of 100 to 200 meters is necessary if moderate braking is to be utilized and protection is required at high speeds. Even emergency use only, assuming .75 g braking, requires a range of approximately [illegible] meters. It is assumed that anti-skid braking systems would be in use on any vehicle equipped with a collision avoidance system.

Trajectory Considerations

Some useful insights into inherent limitations of a simple narrow-beam system, aimed directly ahead of the vehicle, can be obtained by examination of certain vehicle/obstacle trajectories. In this brief analysis a much simplified model is used: uniform accelerations, frictional forces with constant coefficient, and all motion assumed to occur on a planar surface with no rotational vehicular movement.

STRAIGHT-LINE BRAKING

The stopping distance s is given by $s = v^2/2\alpha$, where v is the initial vehicle velocity, and α is the deceleration. For a maximum available deceleration α_m, the minimum stopping distance is then $s_s = v^2/2\alpha_m$. This is plotted in Figure 10 for various α_m. The maximum deceleration normally attainable is .8 to .9 g. s_s is also the required anticipatory sensing distance, assuming braking is automatically initiated at a deceleration of α_m. (An alternative view is to calculate the maximum velocity for which complete stopping is possible, as a function of sensing distance, for various α_m; this, too, may be read from Figure 10.)

BEAMWIDTH

Given a particular maximum required sensing distance (determined by the maximum speed for which the system is intended to provide protection), it is desirable that the radar observe approximately a full lane-width

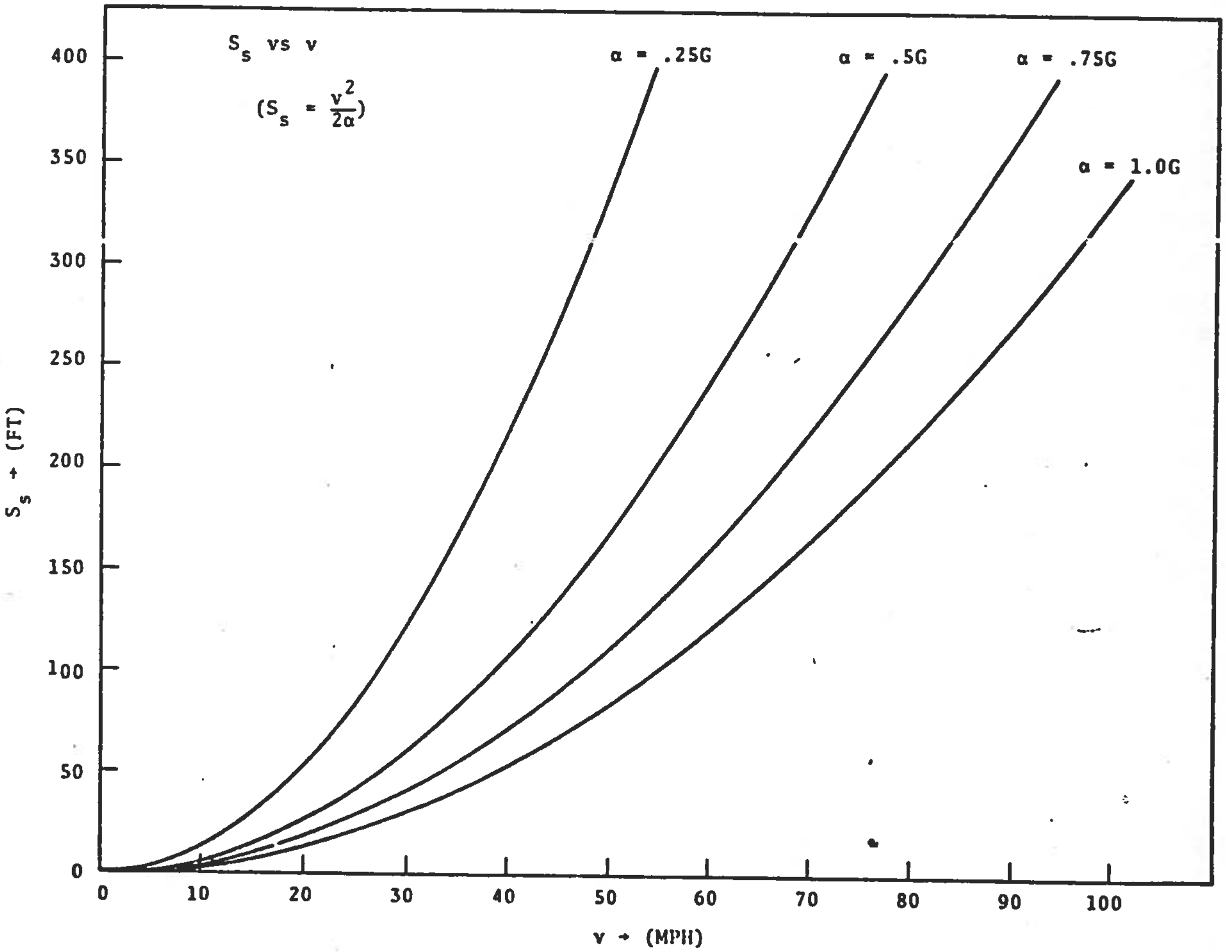


Figure 10. Necessary sensing distance s_s vs. velocity v, for various α_m

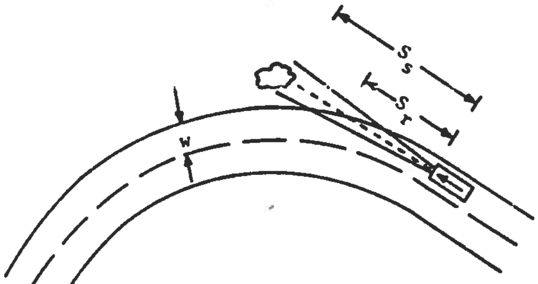
at that distance, and no more, lest roadside objects and vehicles in adjacent lanes be misperceived as hazards. The required beamwidth θ is then given by $\tan(\theta/2) = (w/2)/s_s \approx \theta/2$, or $\theta = w/s_s$, where w is the lane width, e.g., for $s_s = 75$ meters and $w = 4$ meters, $\theta = .053$ rad $= 3.0°$. (It is assumed that there is no attempt to use a scanning antenna or a trajectory-mapping signal processor; it is unlikely that such systems could meet the basic cost constraints.)

CURVED ROADS

One aspect of the narrow-beam requirement is the problem of curving roads: the radar, looking straight ahead, may fail to observe a roadway obstacle, while being alerted by objects not hazardous. It is necessary to consider under what circumstances the required sensing distance, s_s, becomes greater than s_r, the distance at which misalignment by one-half lane-width (the criterion chosen here) occurs, for under such conditions the system cannot operate correctly (see Figure 11a). s_r depends upon the lane width and the road curvature R: $s_r = \sqrt{Rw}$. However, it's useful to express R in terms of the lateral (centripetal) acceleration α_ℓ necessary to cause an object with velocity v to follow a path of radius of curvature R: $R = v^2/\alpha_\ell$. Thus, $s_r = v\sqrt{w/\alpha_\ell}$. The average motorist is quite sensitive to non-zero lateral accelerations, and normally prefers to limit α_ℓ to low values. On curved roads, he does this by limiting his velocity to a value appropriate to the existing $R (\alpha_\ell = v^2/R)$. In essence, sharply curved roads limit the effective radar range to s_r, but also (by enforcing reduced vehicle velocity) reduce substantially the required sensing distance, s_s. At lower speeds, there is thus no problem, but since s_s is proportional to v^2, while s_r varies only as v, the moderately curved roads (permitting higher velocities) present potential difficulties. The condition for satisfactory operation is $s_r \geqslant s_s$ (permissible sensing distance greater than required sensing distance), or $v\sqrt{w/\alpha_\ell} \geqslant v^2/2\alpha_m \cdot v_b$, the maximum (boundary) velocity for which the system can operate as intended, is then given by $v_b = 2\alpha_m\sqrt{w/\alpha_\ell}$. As an example, consider $\alpha_m = .75$ g, $\alpha_\ell = .2$ g, and $w = 4$ meters. Then $v_b = 21$ m/sec = 47 MPH. α_m is quite important here; a system designed to apply only moderate braking encounters this limit at much lower speeds. Highway banking can also significantly increase the tolerable α_ℓ, similarly lowering the boundary velocity for viable operation, i.e., banking can permit speeds sufficiently high—even on sharp curves—that the radar can not "see" far enough ahead to provide protection.

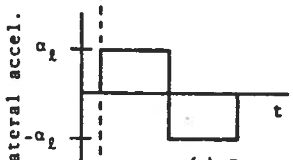
EVASIVE MANEUVERS

A similar problem arises in situations which require abrupt maneuvers, as when avoiding potential collisions by swerving around them. This is indicated in Figure 11b, with two possible approximations to the required lateral accelerations shown in Figures 11c and 11d. In this case, $v_b = 2k\alpha_m\sqrt{w/\alpha_\ell}$,

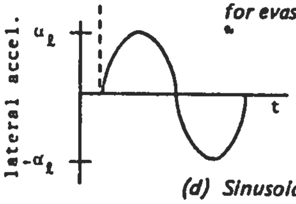


(a) Curved road

(b) Evasive maneuver



(c) Rectangulur acceleration for evasive maneuver



(d) Sinusoidal acceleration for evasive maneuver

Figure 11. Trajectories

with $2 \leqslant k \leqslant \pi$, depending on the lateral acceleration assumed. This appears to indicate that the uniform curve constraint is the more severe. However, a substantially larger α_ℓ might be tolerable in an emergency situation, and w could be somewhat smaller. (The important consideration here is that the radar must not induce severe braking for an obstacle which might more safely be circumvented.)

Experimental Realizations

Most research in this area has been carried out by companies with a proprietary interest, and little of a technical nature has been published. However, a number of comments can be made. There is, of course, a significant similarity between radar crash sensors and collision avoidance hardware, but there are also differences. The bistatic (two-antenna) configuration is not mandatory here, and both monostatic systems (Bendix, Rashid Corp.) and bistatic sensors (AutoStop) have been demonstrated. Range can be estimated from reflected amplitude, but explicit ranging is more often used, typically achieved by use of a frequency modulated or two-frequency (diplex) doppler radar. Direction discrimination—whether the target is approaching or receding—is a necessity. (This is unlike the crash sensor case, in which the receding situation can never involve high enough velocity to cause a problem at the short range in question.) Systems designed only for headway control may choose to disregard fixed objects by comparing closing rate to ground speed, generally available through road back scatter.

A major option in realization is the choice of an independent or cooperative technique. In the latter case, potential obstacles are in some fashion equipped with a transponder which the radar can identify. RCA has demonstrated such a system, in which a special harmonic antenna is mounted on target vehicles and reflects a signal at exactly twice the frequency transmitted. The radar receiver similarly operates at twice the radiated frequency, and is thus insensitive to reflections from all other objects which are at the fundamental frequency. It is thus immune to many of the problems inherent to independent systems—target discrimination, "blinding" by other systems, clutter, etc. However, these benefits are achieved through sharply limiting the number and variety of targets to which the radar is responsive. Thus, the distinction between cooperative and independent radars is not merely technical; quite different functional characteristics result.

Consideration of optimal frequency is a question both technical and economic. Lowest prices are generally found for X-band (10 GHz) components, but antennas of adequate directivity (narrow beamwidth) will be 30 to 60 cm (12 to 24 in.) in diameter, which raises serious installation questions. Thus, both GM and Bendix have constructed automotive radars operating at 35 GHz, for which suitable antennas are approximately the size of headlights. At present, components such as oscillator diodes are far more expensive at this frequency, but this may change with time. The shorter wavelengths also must be examined for performance aspects, such as ground return (apparently reduced), sensitivity to rain, target discrimination, etc.

Performance Considerations

Collision avoidance systems have been demonstrated in recent years which show reasonable basic characteristics. However, analysis of implementation for general usage indicates performance aspects which require comment.

TARGET DISCRIMINATION

The basic target discrimination problem here is quite similar to that for the crash prediction case, and little elaboration is needed. Requirements depend critically upon the operating mode selected. Note that even a cooperative (transponder) system may exhibit such directional characteristics that discrimination becomes highly dependent upon target orientation.

INDETERMINACY

There are many collisions preceded by only the briefest hazardous trajectory, just as many "collision courses" exist only transiently. Substantial and accurate tracking is required, and even this may prove insufficient to deal with occurrences such as cars crossing in front of other vehicles, making turns, yielding (or not yielding) right-of-way, etc. It will not be easy to match the perceptual capabilities and predictive skills of even a sick, inebriated, or inexperienced driver.

RADIATION HAZARD

The greater system range and informational requirements needed for collision avoidance, as compared to crash prediction, make this a more significant question here. For the range capability required 100 mW has been found to provide sufficient signal, and even at 35 GHz, power density at the antenna should be less than 1 mW/cm^2. However, a lowering of allowed levels is possible, and could put such systems into a marginally safe category, particularly for those whose occupations involve continual exposure to automobiles.

PROPAGATION EFFECTS

A signal transmitted to a target and reflected back can travel in other paths than a direct line. Reflected energy arriving from the target via both direct and indirect paths can interfere to produce periodic fading of the signal as the range changes. A similar phenomenon which could generate "false" targets is reflection off other vehicles so that a target appeared to be in a different location than the one occupied (a mirror effect).

BLINDING

At night, a motorist may have difficulty seeing due to the intense high-beam lighting of approaching cars. A radar receiver faces a similar problem when exposed to direct radiation from nearby on-coming vehicles. Detection of true reflections and derivation from them of sufficient information for proper operation can be greatly hindered or even prevented completely.

INTERFERENCE

A given system must be able to distinguish between a reflected return and a signal from another system. Misinterpretation of the received signal could cause an unnecessary emergency brake application. For the crash prediction case, effective countermeasures were found to be relatively simple. However, the greater range and informational requirements of collision avoidance radar make the problem considerably more difficult.

COST

The present ambiguity as to optimal form and function makes difficult accurate estimation of costs. However, the TSC crash sensor studies provide a basis for a rough approximation. The probable need for higher-frequency components, higher power, substantially more elaborate modulation and signal processing, and probable connection to the braking system all make likely a cost increase by at least a factor of 2, and probably 4 or 5—an OEM price in the range of $25 to $75. (Anti-skid braking is assumed already present.) The same multipliers as were invoked previously lead to an estimated life-cycle cost to the consumer of at least $150, quite possibly over $500.

The preceding discussion has hopefully made clear the many distinctions between crash prediction and collision avoidance; it seems unlikely that any significant cost savings are possible through commonality if both were to be installed.

Topics for Further Research

Past research on collision avoidance sensors and systems has tended to concentrate upon specialized units which meet a particular perceived need, often influenced by what is technically feasible for the developer. However, adequate determination of the optimal system—and hence of optimal sensor characteristics—requires a comprehensive and analytical investigation. Topics worthy of inclusion are indicated below, categorized in terms of analysis and engineering tasks.

SYSTEM ANALYSIS

1. Definition of Operating Modes. As a first step toward a comprehensive analysis, it is necessary to define explicitly a reasonable number of operational modes: advisory only, headway control, short-range emergency braking, etc.
2. Development of a Data Base. All available sources of accident data must be examined and utilized to permit an estimate of the potential effectiveness of the various operating modes. Additional data may have to be generated by special studies.
3. Examination of Trajectories. A computer model for examination of normal and abnormal driving trajectories and collision patterns is needed to predict the actual performance associated with various modes.
4. Study of Driver Response. It is necessary to determine the response of a wide spectrum of drivers exposed to automatic systems, under various conditions. Advisory systems are included.
5. Effects on Other Vehicles. Consideration must be given to the effect on other vehicles under all road and traffic conditions. At best, introduction of such systems would entail a long period of partial implementation. A mix of automobile characteristics offers a potentially hazardous situation and must be studied.
6. Effect on Highway Capacity. Presumably, at some level of system implementation, safe headway on high speed roads could be less than is currently the case. A general examination of road capacity as a function of implementation, for various road and traffic conditions, would be of value.

SYSTEM ENGINEERING

1. Specific Problems. Specialists in radar technology should examine the many relevant technical problem areas, including multipath effects, blinding, interference, target discrimination, etc.
2. Optimal Specifications. Optimal range, beamwidth, frequency, and type of radar should be determined for those operating modes which appear to have potential viability.
3. Cooperative vs. Independent Radar. It is not possible at present to reach a conclusion concerning the relative merits of cooperative and independent systems. Certain technical problems are dramatically reduced for the former case, but many targets are then ignored. There is additional cost associated with the transponder, and effectiveness becomes dependent upon *both* elements not only being installed but adjusted and operating correctly. This question, which is of fundamental importance, will require significant efforts in both system analysis and engineering to resolve.
4. Technology Assessment. It is appropriate to analyze and test samples of all currently available collision avoidance systems to gain insight into technology problems and operational characteristics.
5. Cost/Benefit Studies. Approximate estimates of system cost and potential safety benefits, as well as overall reliability predictions, should be carried out for candidate systems and system concepts. Analysis of benefits should include consideration of the impact of other safety improvements recently introduced or mandated for the near future. For example, improved bumper and head-restraints reduce the toll of rear-end collisions, and thus limit the value of preventing such accidents.

CONCLUSIONS

Crash Prediction

Radar crash prediction with good—though far from perfect—accuracy appears to be technically feasible, at a moderate cost. However, ultimate viability depends upon other factors. Basic, of course, is realization of the expected benefits and public acceptability of deployable passive restraints. Further, since the primary value of anticipatory sensing is associated with higher velocity accidents, improved vehicle structures of sufficient basic crashworthiness must be available. Finally, the relevance of true anticipatory sensing is dependent upon developments in bumper-mounted sensors and more rapid deployment of restraint systems. Sufficient progress in these areas could substantially lessen the need for the more expensive and less discriminating radar approach. On the other hand, the advantages of less rapid deployment may give special value to predictive sensing, and the steady trend toward higher speeds may require a faster overall system than can be obtained in any other way.

Collision Avoidance

It is hoped that the preceding discussion has provided some feeling for the complexity of automatic collision avoidance systems. Virtually none of the questions which can be raised as yet have satisfactory answers. Thus, aside from the realization that the subject is not a simple one, no final conclusions can be stated. However, some preliminary observations can be made.

It is particularly clear that technical difficulties increase sharply with the desired range of the system. This includes factors such as target discrimination, out-of-lane targets, curves, evasive maneuvers, intervehicle interference, dynamic range, and blinding. Further, a system which—through long-range sensing—provides low-g braking frequently in normal driving is likely to annoy a motorist to the point of system disablement, or lull him into a false sense of security and—ultimately—an accident. Thus, a system designed only for emergency operation, intended only to apply full braking at the last possible time, and thereby with the shortest possible sensing distance, appears to be optimal in terms of both accident reduction and driver acceptability. For example, a deceleration of .75 g permits a complete stop from 60 MPH in 50 meters (160 feet); in only 30 meters (100 feet) speed can be reduced from 60 MPH to 30 MPH or to a full stop from 47 MPH—a speed which includes a very large percentage of actual accidents.

Given the difficulties associated with the simplest form of radar braking, it appears to be very questionable whether a higher degree of automation—obstacle avoidance through "radar steering," for example—has any hope of practical viability. Determination of the value and desirability of incorporation of a warning device—an alarm—into such a system will require substantial testing of driver response. It would require substantially greater sensing distances to allow several seconds for necessary perception, decision, and action. A high percentage of false alarms could damage credibility. It is unlikely that a system which merely alerts the driver, with no brake actuation, can reduce accidents sufficiently to warrant the cost, since even this limited function will be relatively expensive to provide.

It remains to be demonstrated that a truly effective system is technically feasible within realistic constraints. Many problems pose a severe challenge to the system designer, magnified by the requirements for very high reliability and low cost, with operation in a most challenging environment. Thus, future research in this area should first focus upon questions of feasibility and potential benefits, with the clear understanding that a negative conclusion may result.

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Bibliography

Jones, T. O. et al., *Comparative Analysis of Crash Sensors,* SAE Paper 720035, SAE Automotive Engineering Congress, Jan. 10-14, 1972, Detroit, Mich.

Jones, T. O. et al., *A Critical Review of Radar as a Predictive Crash Sensor,* SAE Paper 720424, 2nd Int. Conf. on Passive Restraints, May 24, 1972, Detroit, Mich.

Takahashi, T. et al., *Development of a Radar Sensor for Inflatable Occupant Restraint System,* SAE Paper 720422, 2nd Int. Conf. on Passive Restraints, May 24, 1972, Detroit, Mich.

Hopkins, J. B. et al., *A Microwave Anticipatory Crash Sensor for Automobiles,* SAE Paper 720423, 2nd Int. Conf. on Passive Restraints, May 24, 1972, Detroit, Mich.

Pujdowski, E., *Crash Sensors for Inflatable Occupant Restraint Systems,* SAE Paper 720420, 2nd Int. Conf. on Passive Restraints, May 24, 1972, Detroit, Mich.

Hopkins, J.B. and F. R. Holmstrom, *Anticipatory Crash Sensors for Passive Restraint Deployment,* WESCON-1972, September 19-22, 1972, Los Angeles, California, Paper 20/4.

Ross, G. F., *BARTS, A New Radar Concept,* Sperry Rand Research Center Research Report SRRC-RP-73-11, May, 1973.

Carp, R. W. et al., *Adaptive Speed Control for Automobiles,* Bendix Technical Jour., Autumn, 1969, pp. 46-56.

Brinton, J., *Radar Braking Is Set for Market Debut,* Electronics, January 5, 1970.

Technical Specifications for Automatic Vehicle Headway Measuring Equipment, Solicitation for Proposals, Road Research Laboratory, Crowthorne, England, 1970.

Harokopus, W. P., *Application of Radar to Automobile Control and Sensing,* Digest, International Microwave Symposium, May 16-20, 1971, Washington, D.C., pp. 168-169.

Baghdady, E. J., *Automobile Radar* Digest, International Microwave Symposium, May 16-20, 1971, Washington, D.C., p. 170.

Hopkins, J. B., *Microwaves and Auto Safety,* NEREM 72 (IEEE) Record, Nov. 2, 1972, Boston, Mass. pp. 301-304.

The Rashid Radar Collision Avoidance System, Technical Data. Bull. No. 1, The Rashid Corp., Mt. Clemens, Mich.

Milner, C. J., Private Communication, Univ. of New South Wales, Kensington, Australia.

Stevens, J. E. and L. L. Nagy, *Diplex Doppler Radar for Automotive Obstacle Detection*, IEEE Vehicular Technology Group 23rd Annual Conference, Dec. 6, 1972, Dallas, Texas. (General Motors Research Publication GMR-1300).

Shefer, J. and R. J. Klensch, *Harmonic Radar Helps Autos Avoid Collisions*, IEEE Spectrum, May 1973, pp. 38-45.