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**National Highway
Traffic Safety
Administration**

Collision Avoidance System Cost-Benefit Analysis

Volume I—Technical Report

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16. Abstract

Collision-avoidance systems under development in the U.S.A., Japan and Germany were evaluated. The performance evaluation showed that the signal processing and the control law of a system were the key parameters that decided the system's capability, in terms of target discrimination, and the ability to avoid false alarms and missed the targets. The benefits evaluation of selected radar systems was conducted using the Kinetic Research Accident Environment Simulation and Projection (KRAESP) Model and an accident data base which was adjusted to be nationally representative. The results indicated that radar braking systems were most effective in the rear impact mode as well as substantial benefits in frontal, vehicle-to-vehicle, and fixed-object impacts. The effectiveness of the radar systems in the side impact mode was very limited. Non-motorist impacts may be avoided by radar braking systems; however, the ability of the radar to detect pedestrians, bicyclists, and motorcyclists needs further study.

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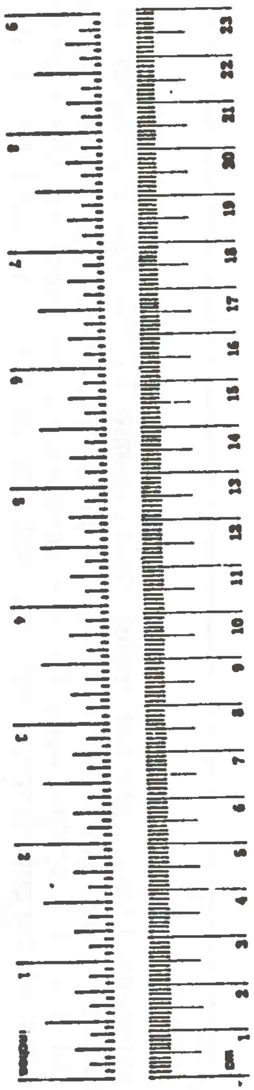
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

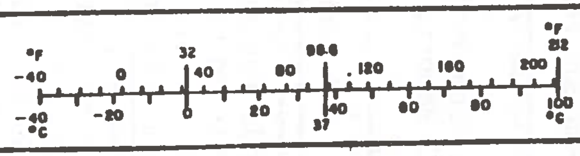
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION AND BACKGROUND

In recent years, several studies have pointed to the fact that human factors were the cause of a large proportion of the accidents when pre-crash accident data were studied. For example, according to tri-level investigation of accident data conducted by Indiana University, one or more human factors were probably the cause of about 93 percent of the accidents. The human factor can be introduced by driver inattention, fatigue or several other factors. A radar collision avoidance system, either a "warning only" type or an "automatic braking with warning" type, can serve as a useful driver aid.

The same accident pre-crash factor studies have shown that on many occasions drivers simply do not take proper accident avoidance action. A radar system with an automatic braking function can aid in either avoiding certain accidents or at least reduce the severity of the accident.

The above arguments were substantiated with results from earlier studies conducted by Bendix Corporation and Indiana University. Both studies concluded that about 18 percent of the traffic accidents could be avoided if radar systems were installed on automobiles.

With this background, the National Highway Traffic Safety Administration (NHTSA) initiated this study to conduct a realistic and more rigorous cost-benefit analysis for various collision-avoidance system configurations. The program emphasized the accurate definition of realistic system performance characteristics and the critical evaluation of technical limitations on target discrimination.

Kinetic Research's efforts on this program started with a critical evaluation of previous cost-benefit analysis studies. Two previous studies done by Bendix Corporation and Indiana University were critically evaluated. The results are presented in Section 1 of this report and were used as important guidelines for the current program.

The next step in the program was the selection of the accident data base and the analytical approach. A series of selection criteria were developed for this task. Available data bases and analytical approaches were evaluated against the selection criteria to make the final selection. The data base used on this program is the North Carolina State Accident Data File for the year 1979. The methodology used is the Kinetic Research Accident Environment Simulation and Projection (KRAESP) Model appropriately updated for this program. The process of the data base and analytical model selection is described in Section 2 of this report.

Section 3 of this report documents the results of the radar system performance study. The reported information was collected by directly contacting developers of the radar collision avoidance systems and by studying the published literature on the subject. Additionally, two overseas trips were made — one to Japan and the other to Germany — to visit the radar system developers in those two countries. Two computer models were developed: one for antenna and the other for target cross-section. The details of the models and the results of the analysis are also included in Section 3.

Section 4 of this report contains the description of the analysis and the results of the benefit evaluation of the selected radar collision avoidance systems. Section 5 summarizes the conclusions and the recommendations of this analytical program. Selected highlights of the results are presented in a technical summary that immediately follows the introduction.

Two types of radar collision avoidance systems considered in this program are:

1. Warning only systems
2. Automatic braking systems.

It is to be understood that the first type does not include any capability on the part of the system to actuate the brakes. The system alerts the driver as to the impending danger and the driver has to apply the brakes. On the other hand, the second type includes the system capability to apply brakes if selected logic and driver action criteria are met.

The primary emphasis of the program has been on the "automatic braking" type of the radar collision avoidance system and control logic equations show term R_B to represent the range at which the radar-induced braking will begin. The "warning only" type of collision avoidance systems are evaluated by allowing for a driver actuation of braking after a selected time delay.

TECHNICAL SUMMARY

The work summarized in this technical summary was conducted by Kinetic Research, a division of Minicars, Inc., under a National Highway Traffic Safety Administration (NHTSA) contract.

In previous NHTSA-sponsored contracts, it has been established that human factors, alone or in combination with environmental and vehicle conditions, have been a leading causal factor of highway traffic accidents. In view of these previous studies, it was suggested that radar collision avoidance systems might be of value in addressing these issues. Therefore, the NHTSA sponsored this study to conduct a cost-benefit analysis of radar braking systems that are currently under development.

The emphasis of this program was on two major areas:

1. The radar system performance evaluation; and
2. The radar system benefit evaluation.

In order to accomplish these objectives, the study included preliminary review of previous radar system cost-benefit analyses and the selection of an appropriate accident data base and evaluation methodology.

The accident data base used on this program was the 1979 State of North Carolina accident data file which was adjusted to be nationally representative. The benefits evaluation methodology used was the Kinetic Research Accident Environment Simulation and Projection (KRAESP) Model. The results of the critical evaluation of previous radar system cost benefits study served as useful guidelines on this program.

The radar system performance evaluation included radar systems available in the U.S.A., Japan, and Germany. The system performance was evaluated for its ability to discriminate between targets, for its capability to avoid false alarms and missed targets, and to collect estimates of production costs. The results showed that the signal processing technique and control laws used were the key parameters that influenced the ability of a system, in terms of target discrimination, and the avoidance of false alarms and missed targets. Based on the available information, the radar systems were classified into three levels based on the sophistication of their signal processing and control laws. These three levels were used for benefits evaluation on this program.

The control laws used in this analysis were:

System One: No radar

System Two: $R_B = 2\dot{R} + S$

System Three: $R_B = \dot{R}^2/2\mu g + \tau \dot{R} + S$

System Four: $R_B = V_1^2/2\mu g - V_2^2/2\mu g + \tau V_1 + S$

System Five: $R_B = V_1^2/2\mu g + V_2^2/2\mu g + \tau V_1 + S$ (head-on only)

(all units in feet, seconds)

where

R_B = Range at which radar braking would begin

$\dot{R}$ = Range Rate or rate of approach of the target

V_1, V_2 = Vehicle Speeds

μg = Potential vehicle deceleration based on the surface coefficient of friction

τ = Radar Time Delay

S = Radar Range Delay

In practice, the analysis was performed for the values $S = 0$, $\tau = 0.1$, and $\mu = 0.5$. In addition, the radar braking range was cut off at 200 feet maximum and the radar system shut off if the vehicle velocity fell below 10 mph. The vehicle braking systems were considered to have an anti-skid feature. The predicted results and the relative benefits are presented in Table 1. The results show that:

1. Radar systems are most effective in rear impact accidents. Accidents avoided are in the range of 26 to 62 percent for the analyzed control laws.

TABLE 1. SUMMARY OF BENEFITS FOR RADAR SYSTEMS SHOWING THE NUMBER AND PERCENT OF INJURIES, ACCIDENTS AND PROPERTY DAMAGE AVOIDED

Radar System Two[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS) 1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
POF	710	11	1.4	16	367	12	151	17	58	17	9	16	7	20	10	18	602	14
POS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ROLL/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	6,270	19	3.9	17	2,042	18	310	17	105	18	93	19	7	23	23	24	2,509	18
VVS	1,122	4	1.1	6	363	4	40	3	30	3	5	3	2	3	6	3	446	4
VVR	2,664	53	1.2	51	1,380	56	65	60	29	67	7	58	2	100	19	76	1,493	56
Ped[4]	487	14	0.2	15	239	13	65	14	43	14	12	15	5	15	42	26	406	14
Total	11,253	7.8	13	12	4,392	14	632	11	256	9	54	10	23	10	100	13	5,457	13

[1] Defined by the control law $R_B = 2\dot{R}$.
[2] Includes accidents with AIS = 0 injuries.
[3] In millions of dollars.
[4] Tabulated for unmodified Vrel.

TABLE 1. (CONT'D)

Radar System Three[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	73	1	1.0	10	149	5	134	15	49	15	9	16	7	20	10	18	358	8
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roll/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	4,802	15	3.4	15	1,612	14	251	14	88	15	19	17	6	19	21	22	1,997	14
VVS	1,084	4	.8	4	356	3	40	3	29	3	5	3	2	3	6	3	438	3
VVR	1,291	26	.7	29	749	30	41	38	14	47	4	33	1	50	16	64	825	31
Ped[4]	419	12	.1	13	202	11	56	12	38	13	10	13	4	12	41	25	351	12
Total	7,669	9	5.9	9	3,032	9	523	9	218	8	47	9	20	9	94	12	3,934	9

[1]Defined by the control law $R_B = \dot{R}^2/2\mu g + \tau\dot{R}$.
[2]Includes accidents with AIS = 0 injuries.
[3]In millions of dollars.
[4]Tabulated for unmodified Vrel.

TABLE 1. (CONT'D)

Radar System Four[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	73	1	1.0	10	148	5	134	15	49	15	9	16	7	20	10	18	357	8
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roll/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	6,018	18	3.5	15	1,884	16	268	15	83	14	15	13	5	16	15	16	2,270	16
VVS	791	3	.6	3	238	2	24	2	17	2	3	2	1	2	4	2	287	2
VVR	3,117	62	1.4	59	1,553	63	70	65	21	70	8	67	2	100	18	72	1,672	63
Ped[4]	462	13	.1	14	225	12	62	13	41	14	11	14	5	15	42	26	386	13
Total	10,561	12	6.6	10	4,050	12	559	9	211	7	46	9	20	9	89	11	4,975	12

[1]Defined by the control law $R_B = V_1^2/2\mu g - V_2^2/2\mu g + \tau V_1$.
[2]Includes accidents with AIS = 0 injuries.
[3]In millions of dollars.
[4]Tabulated for unmodified Vrel.

TABLE 1. (CONT'D)

Radar System Five[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	73	1	1.0	10	149	5	134	15	49	15	9	16	7	20	10	18	358	8
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roll/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	6,255	19	3.8	17	2,001	17	298	16	100	17	20	17	6	19	21	22	2,496	17
VVS	791	3	.6	4	237	2	23	2	17	2	3	2	1	2	4	2	285	2
VVR	3,117	62	1.4	59	1,553	63	70	65	21	70	8	67	2	100	18	72	1,672	63
Ped[4]	479	13	.2	15	234	12	64	14	42	14	12	15	5	15	43	26	400	14
Total	10,715	13	6.9	11	4,177	13	590	10	229	8	52	10	21	9	96	12	5,165	12

[1]Defined by the control law $R_B = V_1^2/2\mu g \pm V_2^2/2\mu g + \tau V_1$ (+ for head-on; otherwise -).
[2]Includes accidents with AIS = 0 injuries.
[3]In millions of dollars.
[4]Tabulated for unmodified Vrel.

2. Vehicle-to-vehicle front impacts and fixed object front impacts are next in order. Accidents avoided in these two modes are in the range of 16 to 30 percent for the analyzed control laws.

3. Non-motorist impacts are next in order and the results show significant benefits. However, the ability of the current radars to detect pedestrians, bicyclists, and motorcyclists is questionable, and the results should be treated as hypothetical benefits. Accidents avoided are in the range of 12 to 14 percent for the analyzed control laws.

4. The current radar systems show very little benefit for side collisions. Accidents avoided are in the range of 3 to 4 percent.

5. Property damage reduction for the analyzed control laws was in the range of 5.9 to 12 million dollars. In terms of percentages, the reduction is in the 9 to 19 percent range.

6. Injuries and fatalities avoided are in the range of 9 to 12 percent for the analyzed control laws.

7. Due to the complexity of the radar systems under study and their developmental status, it was difficult to obtain specific cost estimates; therefore, current best estimates were utilized.

8. The cost-benefit results that are presented are based on the benefits that are derived by adding property damage avoided (in 1979 dollars) and societal costs of injuries and fatalities avoided (in 1979 dollars). The benefits thus derived are compared with the best estimates of radar system costs to arrive at the cost-benefit figures. The conclusion of the cost-benefit trade-off analysis is that radar system benefits are equal to or slightly less than the cost of implementing such systems. (See Table 2.)

9. Estimates of benefits of anti-skid braking systems were derived by considering the improved stopping capability of the anti-skid equipped vehicles.

TABLE 2. SUMMARY OF COST BENEFIT PERFORMANCE OF RADAR SYSTEMS IN 1979 DOLLARS (MILLIONS)

	System 2	System 3	System 4	System 5
All Automatic Braking System				
Total Per Vehicle Benefit				
Non-motorists excluded	34	28	29	31
Non-motorists included	45	38	40	42
Per Vehicle Per Year Life Cycle Cost	45	45	45	45
Per Vehicle Net Benefit (Loss)				
Non-motorists excluded	(11)	(17)	(16)	(14)
Non-motorists included	0	(7)	(5)	(3)
Warning-Only Radar System (0.4 second delay)				
Total Per Vehicle Benefit				
Non-motorists excluded	28	17	26	27
Non-motorists included	29	21	27	28
Per Vehicle Per Year Life Cycle Cost	27	27	27	27
Net Benefit (Loss)				
Excluded	1	(10)	(1)	0
Included	2	(6)	0	1

SECTION 1
COMPARATIVE EVALUATION OF PREVIOUS COST-BENEFIT ANALYSES

1.1 INTRODUCTION AND BACKGROUND

Introduction

This section contains the results of a critical and comparative evaluation of previous radar system cost-benefit analyses.

The objectives of the critical evaluation were:

- To study statistical validity and quality of the data bases used;
- To identify various assumptions, definitions and simplifications used;
- To ascertain if such assumptions, definitions and simplifications resulted in any biases in the results; and
- To evaluate if the previous approaches can be used, with modification, if necessary on this program.

In this section, we evaluate accident data bases (Section 1.2) and the analytical approaches (Section 1.3) used by Bendix, Indiana University and Kinetic Research to assess their applicability to this program. Section 1.4 reviews the results obtained in the Bendix and Indiana studies. A full bibliography of reviewed technical publications is included as Appendix A.

Background

It is well known that, in a significant fraction of automobile accidents, drivers did not apply their brakes or applied them too late to avoid the accident. Various high technology systems have been suggested as mechanisms that could help to reduce the occurrences of these accidents. One technique is the use of anti-skid brakes, while another is the use of radar systems which can sense a hazardous situation when the driver, for whatever reason, does not. Radar can function either to warn the driver of dangerous situations or actually apply the vehicle's brakes, or both. Understandably, a primary concern of radar braking systems is the possible occurrence of false alarms which could apply the brakes under the wrong circumstances.

Several studies have been made which demonstrate the feasibility of radar and anti-skid systems. Consequently, more attention is now being focused on questions concerning their implementation into the vehicle population. One important question addressed here is whether the probable benefits of these systems justify their costs. The benefits include lives saved, injuries prevented or reduced in severity, and reduced property damage. Costs include developing, producing and maintaining the systems, as well as accounting for any fatalities, injuries and property damage caused by the systems themselves.

We reviewed the literature for the purposes of identifying previous works that studied the benefits of collision avoidance systems in order to use it as a basis for a more comprehensive treatment. Only two in-depth analyses were found: the Bendix "Phase II Radar Braking Study" (Refs. 1 and 2) and the Indiana "Tri-Level Study" (Refs. 3 and 4). Another applicable analytical tool was the Kinetic Research BRAKE Algorithm (Ref. 5) which was developed during the NHTSA Research Safety Vehicle (RSV) Program but was never employed in a comprehensive analysis.

1.2 ACCIDENT DATA BASE

To accurately predict the benefits which collision avoidance systems would accrue if they were installed in automobiles, a data base must be selected that satisfies the following three criteria:

- It must be nationally representative;
- It must include information that adequately describes the crash conditions — vehicle traveling and impact velocities, direction and area of impact, presence or absence of braking etc.; and
- It must include measures which will facilitate the reliable evaluation of societal loss.

The following paragraphs briefly describe the accident data used in the Bendix and Indiana studies.

Bendix Study

The accident data base used in the Bendix Study is composed of data from several states. There are several notable general issues associated with the use of state accident data and several with regard to the way in which it was utilized. The general issues are briefly reviewed below and followed by a discussion of the issues associated with the use of the data.

The use of state accident data raises the issues of:

- Representativeness;
- Reporting thresholds;
- Under-reporting of specific accident types;
- Accuracy of many variables in the accident reports; and
- Large amounts of missing data.

In addition, the data used reflect the accident environment in the pre-fuel crisis days. The effect of this is that the tails of the velocity distributions corresponding to high velocities are now shifted towards lower velocities. This shift will likely change the projected benefit. Further, it may be that the travel patterns represented have now changed (i.e., a higher fraction of driving is now urban) which will affect the results. Of note is that the fraction of fatalities in the side mode is now much higher relative to the front than it appeared to be in 1973. It is also noted that the vehicle mix has changed notably since 1973.

It is of note that the use of different data files for various data elements can lead to significant distortions if sufficient care is not exercised. Using velocity distributions from one state and other distributions from other states may be particularly dangerous.

One last note is that we are very concerned about the meaning/consistency of the data used with regard to the conditional cumulative velocity distributions, particularly with respect to the meaning of the "vehicle velocity."

Indiana Study

The data base used in the Indiana Study is from a small, localized sample and is very unlikely to be nationally representative.

1.3 METHODOLOGY OF ANALYSIS

The Bendix, Indiana and Kinetic Research methodologies were reviewed to determine their accuracy, reliability and adequacy for use in an upgraded cost-benefit study. The methodology eventually selected for use consisted of an existing model with appropriate modifications. While reviewing the methodologies, we paid special attention to the following items:

- Compatibility. The methodology must be compatible with the data base selected for study.
- Target Acquisition. Determining if and when a radar system acquires a target and initiates brake actuation is a difficult but crucial task. Accurate simulation of target acquisition is also an essential prerequisite to understanding the trade-offs between false alarms and missed targets.
- Accrual of Benefits. The methodology must be able to produce reliable estimates of societal costs (fatalities, injuries and property damage) from the given parameters used to characterize accidents.
- Vehicle Population Trends. The methodology must have the capability to account for future changes in the makeup of the vehicle population, especially the shift from large to small cars.
- Crashworthiness Performance. It should also be able to account for future changes in vehicle crashworthiness.
- False Alarms. While false alarms are highly undesirable, there is no consensus on what levels of occurrence are tolerable and what performance sacrifices are warranted to achieve these levels. Thus, a methodology which could quantify the costs of false alarms would be of great value since it would allow the study of the trade-off between false alarms and missed targets.

- Anti-skid Braking. Most hypothesized collision avoidance systems also incorporate anti-skid braking to help retain control of vehicles. Hence, a methodology which also quantified the benefits of anti-skid brake systems would also be highly desirable.
- Cost. A final requirement, of course, was that the cost of implementing the methodology remain within the scope of this program. The methodology, therefore, must be efficient and not inordinately complex or sophisticated.

The three methodologies of interest are discussed below.

Bendix Model

The Bendix Study provides a very comprehensive treatment of some aspects of the problem. Bendix evaluated thirty-six (36) possible system configurations consisting of all possible combinations of the parameters listed below:

- Range (100, 200 and 300 feet);
- Brake system activation (automatic and driver initiated);
- Brake system type (standard and anti-skid); and
- Radar recognition delay (23, 11.5 and 0 feet).

The "radar recognition delay" represents an extra time allowance given to the radar processor in which to analyze its data before actuating the brakes. Its mathematical significance in the model is that it reduces the range.

To reduce the inconvenience associated with brake activation in parking lots and similar environments, each system is constrained so that it will not operate if the vehicle speed is less than 10 mph.

A basic view of the model is given in Figure 1-1. The model does not study a data base directly; rather, it uses information obtained from a data base to run a simulation. Random numbers are drawn to define the following accident parameters in the order listed:

- Type (rear-end, head-on, angle, bicyclist/pedestrian or fixed object);
- Road condition (dry, wet or icy);
- Road geometry (straight or curved);
- Target size (small, medium or high);
- Number of people killed or injured; and
- Initial velocity.

For example, the first random number might define an accident as being a rear-end type. The chance of a rear-end being chosen equals the fraction of rear-end accidents in the data base. Next, a second random number is drawn to specify the road condition. The probability of specifying a dry road then would equal the fraction of rear-end accidents in the data base which occurred on dry pavement. The process continues through the tree until all of the above variables are specified.

After an accident has been specified, the radar evaluation process begins. The idea is simply to ascertain what would happen if each of the candidate collision avoidance systems were operating in the case vehicle under the same conditions.

Bendix studied the target acquisition problem in some detail, first by analyzing radar cross-section measurements of several targets ranging in size from a child to a large truck. In each case, they found that the various measurements of a given target (e.g., a bicyclist at different angles and positions) fit a log normal distribution, and calculated the mean cross-section and variance for each target. The targets were then grouped into three classifications (small, medium, and large), and a mean cross-section and variance were calculated for each group. The groups are shown in Table 1-1.

The Bendix model uses this information to assign a cross-section, on a random basis, to a target of known size (small, medium or large) at known range. The return signal strength is then directly calculated from the range and cross-

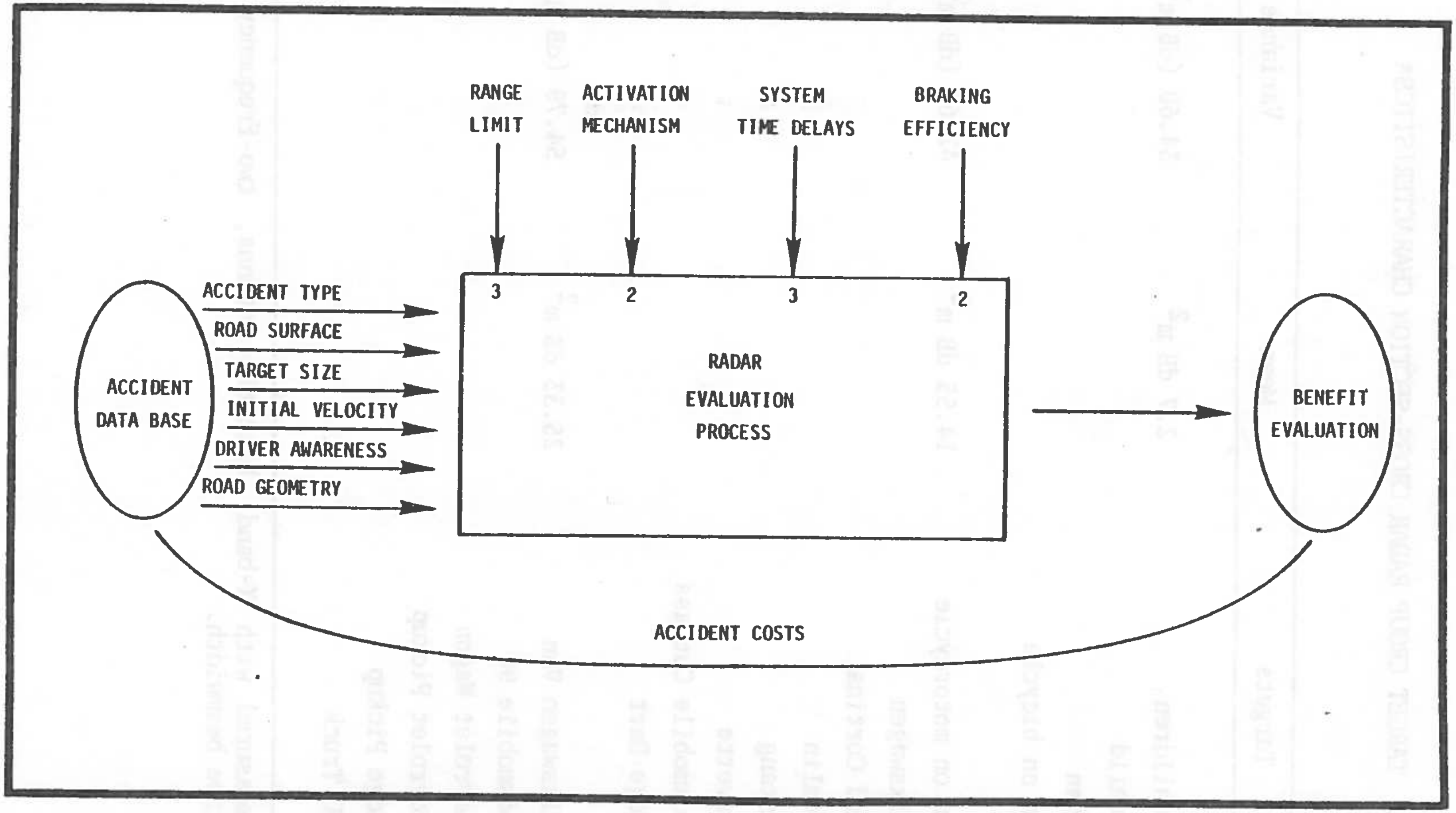

FIGURE 1-1. SIMULATION MODEL FOR THE SENSITIVTY ANALYSIS

TABLE 1-1. TARGET GROUP RADAR CROSS-SECTION CHARACTERISTICS*

Group	Targets	Mean	Variance
Small	3 children	2.7 dB m^2	34.60 (dB $m^2)^2$
	1 child		
	1 man		
	Man on bicycle		
Medium	Man on motorcycle	14.55 dB m^2	42.62 (dB $m^2)^2$
	Volkswagen		
	Ford Cortina		
	Gremlin		
	Mustang		
	Corvette		
	Oldsmobile Cutlass		
	Dodge Dart		
Large	Volkswagen Van	25.33 dB m^2	54.79 (dB $m^2)^2$
	Oldsmobile 98		
	Chevrolet Wagon		
	Chevrolet Pickup		
	Dodge Pickup		
	GMC Truck		

*Cross-sections measured with X-band, bistatic antenna, two-frequency CW radar with 5 degree beamwidth.

section, and compared to a detection threshold. If the signal strength exceeds the threshold, the system assumes that a target exists. The threshold was defined such that 70 percent of all large targets at 300 feet would be detected.

Bendix also considered the very common situation where a target's cross-section varies with time. As a target moves toward the radar (or vice versa), its radar cross-section will vary and cause the probability of detection to change. To address this question, Bendix reviewed the data from Reference 6 and found that typical correlation distances ranged from a few feet for pedestrians walking toward the radar to 75 feet for some vehicles. The correlation distance of radar cross-section is the average minimum distance that range must change in order that measures of cross-section be effectively correlated. To simplify the problem, a 50-foot correlation distance was assumed for all targets.

Based on the analysis briefly described above, Bendix constructed continuous curves that define the cumulative probability of detection as a function of range. Nine (9) separate curves are given which show the three (3) target sizes and three (3) initial acquisition ranges (100, 200, and 300 feet). All medium and large vehicles are assumed to enter the radar's field of view at maximum range. However, this assumption was not made for small targets since the data showed that a significant fraction of them enter the field-of-view at shorter ranges. To accommodate this, the model assumed that only a fraction of small targets would enter the field-of-view at maximum range and be detected. In other cases, no benefits were accrued.

The Bendix model grouped accidents into five types: rear-end, head-on, angular, bicyclist/pedestrian, and fixed object. The targets in rear-end, head-on, and angular accidents were assumed to be either medium or large depending on the frequency of occurrence in the data base. Targets in bicyclist/pedestrian and fixed object accidents were assumed to be small.

The following equation is used to determine if the object's range and range rate warrant brake actuation:

$$\text{Is } R - 2\dot{R} \leq 0?$$

where R represents range (in feet) and $\dot{R}$ represents range rate (in feet/sec). Depending on R, $\dot{R}$, and the road condition, the brakes may stop the vehicle in time to avoid an accident or may only reduce the severity of the accident. The selection of this activation equation is puzzling. Other approaches typically activate when R and $\dot{R}$ are such that a certain deceleration (0.5 G, for example) is required to prevent a collision. In such cases, $\dot{R}^2$ is used. False alarm considerations are expected to make an alternate control law more appropriate.

The model also allowed a time delay before the brakes became fully activated. The delays were 0.1 second for automatic braking and 0.9, 1.5, and 2.7 seconds for sober, drinking, and drunk drivers who are alerted by warning systems.

To include the effects of anti-skid brakes, Bendix made stopping distance a function of the brake system as well as road condition. Anti-skid systems reduced stopping distances by 0 percent on dry surfaces, 10 percent on wet surfaces, and 15 percent on icy surfaces. Unfortunately, the model does not consider the added benefits of improved vehicle controllability.

For angular (side) accidents, the model searches to see if the damage area of the target vehicle is in the front, middle or rear third. For the first case, it assumes that the target is not in the radar field-of-view long enough to affect the outcome. For the two latter cases, it conducts a simplified analysis to determine if the collision would have been avoided.

In all cases, road curvature limited the radar acquisition range to certain distances. The range was not limited on straight roads except for fixed object accidents and, as we have already mentioned, pedestrian/bicyclists.

Bendix assumed that an average vehicle would have a useful lifetime of nine (9) years. They also developed a utility schedule which accounted for variations in vehicle use with age. However, they did not allow for changes in either the total size or the mileage (small vs. large) of the vehicle fleet.

The monetary values used for the savings ascribed to reduced fatality, injury, and property damage were supplied by the NHTSA, and are given below:

Fatality	$242,000
Injury	7,000
Property Damage	360

A 10 percent discount rate was applied to future benefits.

Problems arise with the model's recreation of head-on accidents. The technique is to pick, at random, two impact velocities which then define a closing velocity. The rate of deceleration is doubled assuming that both vehicles have radar braking. This assumption is justified if both vehicles are traveling at the same velocity, say 30 mph, but not if one vehicle is traveling at a higher speed, say 40 mph and 20 mph. In this case, one vehicle would stop decelerating before the other and the doubled rate of deceleration would no longer be valid. In some instances, then, the model will mistakenly show accidents to be avoided. Three specific additional problems are described below.

The description of the model in the text of Reference 2 is inconsistent with its actual implementation in the computer program. Specifically, the report describes the process as first determining velocities, and then the number of injuries and fatalities. Rather, the model as implemented first determines the number of fatalities and injuries, and then the velocity.

For example, if there is a fatality, a random number is selected and a bin number is determined which corresponds to a velocity — the velocity used to represent this bin is (10.*(BIN# - 1) + 4.5). Presumably, the velocity is being selected from data representing a conditional cumulative distribution of fatalities as a function of velocity.

There is an issue with regard to what this data actually is since the concept of "vehicle velocity" in a two-vehicle impact is not obvious (i.e., how does one derive the cumulative percent of all fatalities as a function of velocity if the velocity refers to one vehicle?). Thus, there is a question with regard to whether that data was meaningfully prepared and/or consistently used. Ignoring this point, one might expect that the data used and illustrated in Reference 2 can be represented as shown in Figure 1-2.

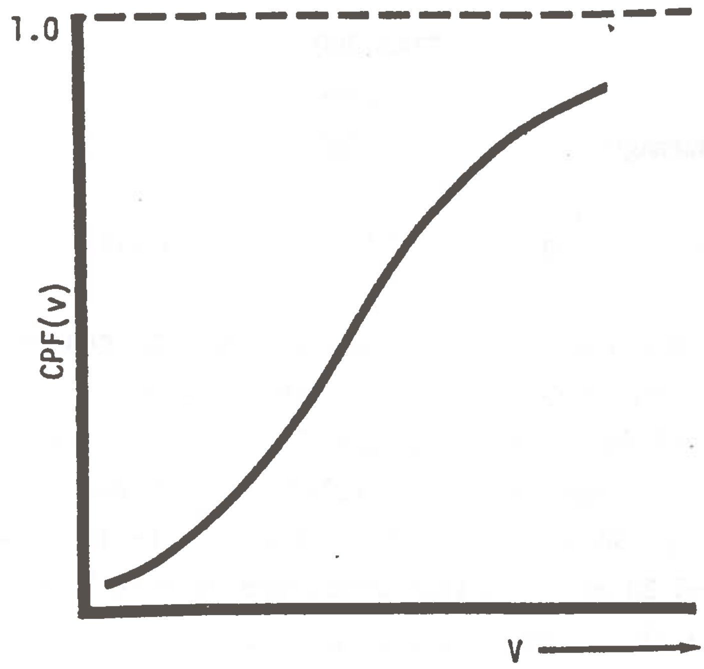

FIGURE 1-2. CUMULATIVE PERCENTAGE OF FATALITIES AS A FUNCTION OF VEHICLE VELOCITY

$$CPF(v) = \frac{\int_0^V P(FAT|v)F(v)dv}{\int_0^\infty P(FAT|v)F(v)dv} \qquad \text{eq. (1)}$$

The model first identifies a baseline consequence (i.e., number of fatalities, etc.) and then infers the velocity. So far, this would not be unacceptable. The model then computes a new impact velocity and computes the benefit for each of the various systems. To compute the benefit, the algorithm first looks up the same data described in equation (1) above and, for example, where a fatality occurred, computes the difference (PSAV) in the cumulative percentages of the old and new velocities, draws a random number and, if the number drawn is less than PSAV, the fatality is assumed not to occur. (It would become an injury.) The problem is that it is incorrect to say that the probability of averting a fatality equals the difference in the cumulative probability of fatalities at the two velocities. That is, the fraction, PSAV, being computed in the model appears to be:

$$PSAV = \frac{\int_{0}^{v_I} P(FAT|v)F(v)dv - \int_{0}^{v_F} P(FAT)|v)F(v)dv}{\int_{0}^{\infty} P(FAT|v)F(v)dv} \quad \text{eq. (2)}$$

Hence

$$PSAV = \frac{\int_{v_F}^{v_I} P(FAT|v)F(v)dv}{\int_{0} P(FAT|v)F(v)dv} \quad \text{eq. (3)}$$

Clearly what is desired is the change in the probability of being a fatality. It appears that the data is confounded by the presence of F(v). The only way to get to the probability in a way which is consistent with the use of the data in equation (1) would be if the velocity distribution were assumed to be uniform (i.e., there is an equal probability of any impact speed occurring) – clearly, an inappropriate assumption.

Thus, three points are identified. These are summarized below:

- A strong possibility exists that the data used is being inappropriately applied through misuse of the concept of "vehicle velocity."
- One of the following appears to be the case:
  - The benefits are derived in a manner inconsistent with the derivation of velocity through misapplication of the cumulative distributions; or
  - A uniform velocity distribution is assumed for accidents.
- The report in Reference 2 appears to incorrectly describe the process the algorithm actually goes through to derive benefits – in particular, the model does not first derive a velocity, and then the number of injuries and fatalities – rather it determines the number of

injuries and fatalities, and then derives the velocity for the accident.

A final shortcoming in the methodology is its use of closing velocity as a predictor of accident cost. Velocity change (Delta-V) has been shown to be much better for this purpose, and if we are going to account for large and small cars, it is probably required.

We now briefly summarize the Bendix model's strengths and weaknesses with respect to the previously listed requirements:

- Compatibility. An attractive feature of the Bendix model is its compatibility with a wide selection of data bases. It only requires probability distributions of each of the variables discussed above and allows us to obtain the distributions from several different sources if desired.
- Target Acquisition. The model's target acquisition methodology represents the best treatment of this phase of the problem that we have seen. Bendix constructed the target acquisiiton probability curves from data in Reference 6 and it might be worthwhile to perform a brief sensitivity analysis on that data.
- Accrual of Benefits. The Bendix methodology has serious shortcomings in this regard which are discussed above. Also it appears that the model assumes all vehicles have radar.
- Vehicle Population Trends. The model is designed to study a steady-state environment. No provision is included for future vehicle population trends.
- Crashworthiness Performance. Likewise, no provision is included to account for changes in vehicle crashworthiness.
- False Alarms. The Bendix model does not adequately account for the false alarm problem. The model does not calculate direct costs from false alarms; instead, it addresses the false alarm problem by evaluating systems with different performance levels. The implicit assumption is that some reduced performance level exists at which the false alarm problem becomes negligible. However, the radar activation control law used appears to be inappropriate.

- Anti-skid Braking. Another shortcoming of the model is that it ignores most of the potential benefits of anti-skid braking. It includes a provision for reduced stopping distances on wet or icy surfaces but anti-skid systems are not installed for that purpose. Rather, they are installed primarily to help the driver retain control of his vehicle under hard braking. The model ignores these benefits.
- Cost. The cost of implementing the model is within the scope of the program.

Indiana Study

The Indiana University "Tri-Level" Study enlisted a team of multidisciplinary experts to examine a data base containing 215 accidents on a case-by-case basis. They recreated each accident as it would likely have occurred with ten (10) different combinations of these systems:

- Cooperative and noncooperative radar warning. (A cooperative system is one in which all vehicles have a special tag to return the radar signal.);
- Cooperative and noncooperative radar actuated brakes;
- Rear wheel anti-skid brakes; and
- Four wheel anti-skid brakes.

For each accident using each system combination, the team ascertained the likelihood of the accident being: (1) avoided; or (2) reduced in severity. A reduction in severity was defined to occur when the case vehicle's impact speed was reduced by at least 25 percent. (They further required that the reduction in impact speed be at least 10 mph.) The likelihood of either (1) or (2) occurring was defined as either "certain" (probability of outcome > 0.95), "probable" (0.95 > P > 0.8), "possible" (0.8 > P > 0.2) or "highly unlikely" (P < 0.2). After evaluating each accident, they were able to determine the fraction of all accidents which were certainly, probably and possibly avoided or reduced in severity.

Some of the more important assumptions used in the methodology are listed below:

- The radar has a maximum range of 300 feet and a beamwidth of 2.5 degrees;
- The radar issues a warning to the driver when a 0.2 G deceleration is required to avoid hitting the target and, for systems with automatic brake actuation, applies the brakes when a 0.5 G deceleration is required;
- For cooperative systems, all vehicles were assumed to be equipped with a special tag in the centers of their rear faces;
- The radar systems could not detect pedestrians at ranges greater than 125 feet;
- The radar systems were assumed to be free of false alarms even if nonthreatening objects met the other activation criteria;
- No cutoff speed was employed; the radar could potentially activate at any finite case vehicle speed;
- All radar systems were also assumed to perform a headway control function which would help to avoid accidents by eliminating tailgating. Case vehicle following distances were adjusted accordingly. The report states, "The minimum distance one vehicle could follow another on a straight roadway was a function of the relative speed between the two vehicles and the assumption that actuation of the braking system at that speed would occur independent of the driver where $\mu = 0.5$." Exactly what this means is not clear to us but it is significant that the authors have included the effects of headway control in their analysis; and
- A rear wheel anti-skid brake system reduced stopping distances 5 percent on wet pavement and 10 percent on icy pavement. Ten (10) percent and 15 percent reductions were assumed for four wheel systems. Neither system affected stopping distance on dry pavement.

The benefits of rear wheel anti-skid brakes accrued from: (1) reduced stopping distances (as indicated above); and (2) avoidance of rear wheel lockup which led to control losses. The main attribute given to four-wheel anti-skid systems was the ability to maintain steering control when the driver applied sufficient brake pressure to lock the front wheels under ordinary circumstances. During anti-skid braking, the vehicle was assumed to have a maximum cornering capability of 0.5 Gs or 0.8μ, whichever was less. The vehicle's evasive path was not circular – its radius of curvature decreased as the vehicle decelerated. Before anti-skid braking was assumed to have a beneficial effect, the methodology asked the following questions:

- Was a clear evasive path open for escape?
- Did the case vehicle driver apply a steering input in the direction of the evasive path?
- Did the existing tire/road condition permit a sufficient lateral acceleration to perform the evasive maneuver?

These questions were used to ascertain the likelihood of a four-wheel anti-skid system avoiding an accident.

The researchers reconstructed each accident using scaled diagrams and plastic overlays. This technique was particularly useful for studying the effects of hills, curves, trees, etc. on the radar field-of-view. Clearly, examining individual cases by experts has an obvious advantage: it allows a flexibility in decision-making that is difficult to obtain in a computer program. Rather than attempt to anticipate all possible contingencies beforehand, the researchers can handle them as they arise.

The methodology's performance with respect to the previously listed requirements is summarized below:

- Compatibility. The methodology requires a data base containing considerable detailed information about each accident.
- Target Acquisition. When examining cases on an individual basis, experts can achieve insights into the target acquisition problem that would be difficult to achieve with a computerized methodology. The Indiana Study's methodology could benefit, however, by incorporating probability of detection functions similar to those used in the Bendix study.
- Accrual of Benefits. Our criticism of the Bendix Study's detection of a crash severity indicator also applies here (the Indiana team used

impact velocity). Again, we submit that velocity change would be preferable. Moreover, their methodology stopped after calculating the numbers of accidents avoided or mitigated — reductions in injuries, fatalities and property damage were not determined.

- Vehicle Population Trends. The methodology did not address this topic.
- Crashworthiness Performance. This topic was not addressed.
- Anti-skid Braking. The methodology represents the best treatment we have seen for quantifying the benefits. It may be impractical, however, for computerized studies.
- Cost. Examining cases by experts becomes prohibitively expensive when the number of cases becomes sufficiently large. Conversely, for a small number of cases, it becomes relatively inexpensive.

KRAESP Program/BRAKE Algorithm

Kinetic Research constructed the Kinetic Research Accident Environment Simulation and Projection (KRAESP) Model to study proposed changes in Federal safety standards regarding passive restraints, improved side structures, etc. Kinetic Research also developed a special algorithm, entitled BRAKE, to quantify the benefits of radar-actuated brakes.

The outputs of the KRAESP Model are of the expected numbers of fatalities and injuries at various levels of the Abbreviated Injury Scale (AIS).* These numbers are presented for the:

- Year of impact;
- Vehicle size class;
- Vehicle manufacturer;
- Vehicle model year;
- Impact mode (vehicle-to-vehicle or fixed object);
- Vehicle damage area (clock position); and
- Occupant seat position.

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*Developed by the American Medical Association.

This complexity of output represents a very high degree of sophistication.

The user of the model must specify one or more implementation schemes. An implementation scheme consists of a specific mix of vehicle crash management systems for each:

- Vehicle size class;
- Vehicle manufacturer;
- Vehicle model year; and
- Occupant seat position.

A vehicle crash management system is the combination of the restraint system (belt, airbag, etc.) and the vehicle structural characteristics that affect the occupant during the crash (accelerations, force loads, etc.). Its performance is usually specified in the form of dummy injury measures, taken as functions of:

- Impact mode;
- Damage area;
- Crash severity; and
- Seat position.

Crash severity is typically measured by a vehicle's velocity change (Delta-V) during an accident although other measures, such as vehicle crush, may also be used. The model also uses the following data:

- Vehicle population statistics and weights from 1952 to the present;
- Vehicle population statistics and weights for new vehicles in future model years;
- An injury severity (AIS) probability distribution in terms of vehicle class, impact mode, damage area, seat position and Delta-V for unrestrained occupants;
- A probability distribution which subdivides the total number of accidents into cells defined by relative velocity (Vrel), impact model and damage area (referred to simply as a "Vrel distribution"); and

- Other pertinent data (occupancy rates, restraint usage rates, etc.).

The KRAESP program contains default values for many of these inputs. For example, future vehicle sales and market shares are estimated by extrapolating data from the 1976 and 1980 model years, and AIS distributions are compiled from NCSS data. The selection of the data and default values are governed by the circumstances of each application.

The BRAKE algorithm works in conjunction with the KRAESP Model to determine to what extent advanced braking systems reduce impact speeds (or avoid accidents altogether) and to compute the estimated reductions of injuries and fatalities after such systems are introduced into the automobile population. The BRAKE algorithm was especially designed to evaluate advanced, radar-activated braking systems. Its input includes measures of the radar activation range and of the brake system performance (maximum deceleration). The algorithm makes a number of assumptions about how, when, and under what conditions the system operates, and is constructed so that these assumptions can be easily changed as circumstances dictate.

The algorithm processes a data file on a case-by-case basis. For every accident, BRAKE first determines if the advanced braking system would have had any effect and, if it would, then calculates a new impact speed (which may equal 0). After evaluating each case, the algorithm compiles two Vrel distributions for the accident file — one with and one without the braking system. The user can use these distributions as they come out or can input them into the KRAESP Model (preferably after smoothing the data). Figure 1-3 gives an overview of the algorithm.

Some of the more important assumptions made by the BRAKE algorithm are:

- Only case vehicles are equipped with the system;
- The radar will activate the brakes only on straight, flat roads;
- The radar will activate the brakes only in colinear collisions. For a collision to be colinear, the case vehicle must have sustained its primary damage in the 12 o'clock position and, in vehicle-to-vehicle

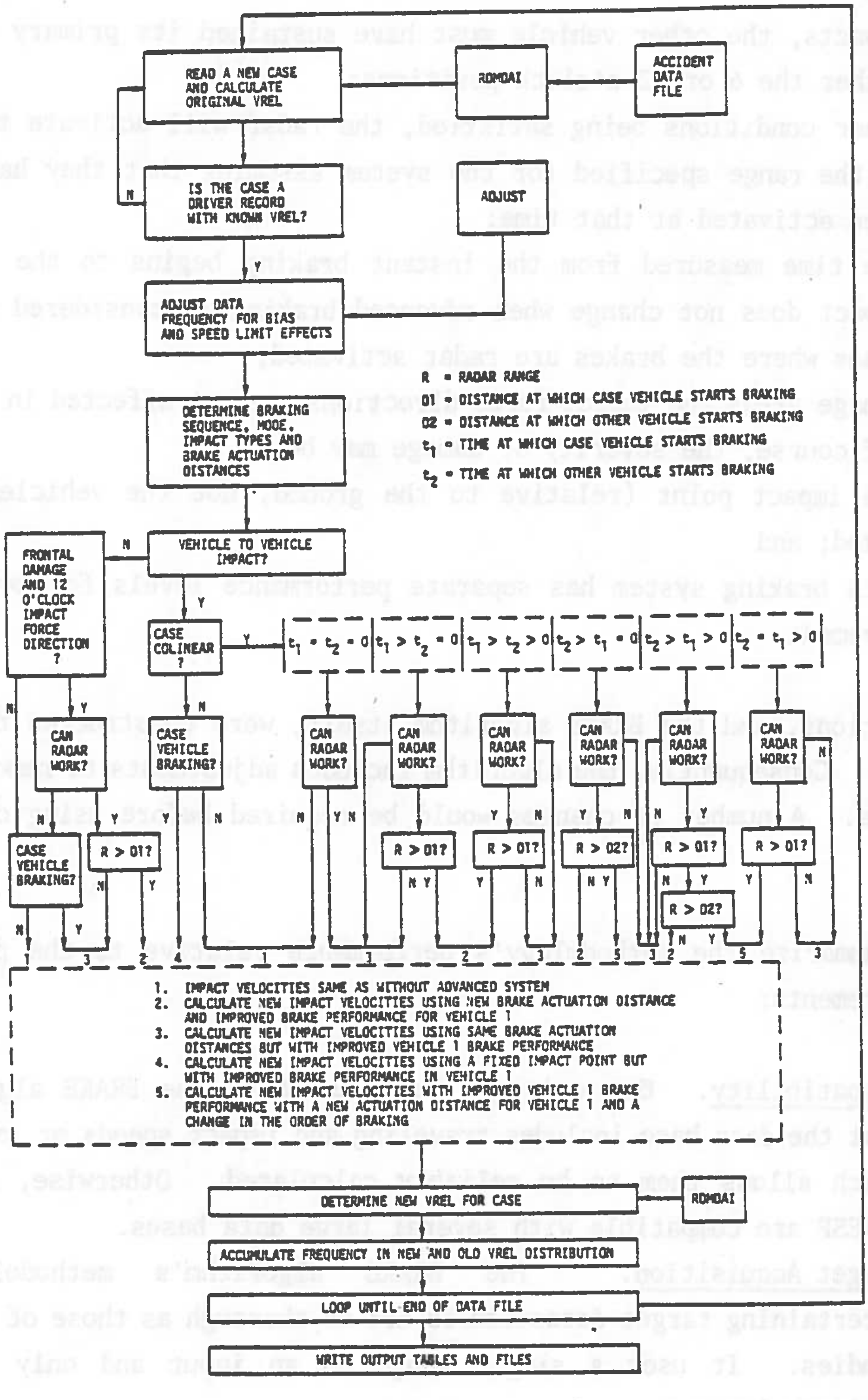

FIGURE 1-3. OVERVIEW OF BRAKE ALGORITHM

impacts, the other vehicle must have sustained its primary damage in either the 6 or 12 o'clock positions;

- Other conditions being satisfied, the radar will activate the brakes at the range specified for the system assuming that they had not yet been activated at that time;
- The time measured from the instant braking begins to the moment of impact does not change when advanced braking is considered except in cases where the brakes are radar activated;
- Damage areas and impact force directions are not affected in any case. (Of course, the severity of damage may be.);
- The impact point (relative to the ground, not the vehicle) remains fixed; and
- Each braking system has separate performance levels for wet and dry pavement.

These assumptions, and the BRAKE algorithm itself, were constructed to process the MDAI file. Consequently, the algorithm includes adjustments to remove biases in those data. A number of changes would be required before using other data files.

Again, we summarize the methodology's performance relative to the previously listed requirements:

- Compatibility. One critical requirement of the BRAKE algorithm is that the data base includes traveling and impact speeds or information which allows them to be reliably calculated. Otherwise, BRAKE and KRAESP are compatible with several large data bases.
- Target Acquisition. The BRAKE algorithm's methodology for ascertaining target detection is not as thorough as those of the other studies. It uses a single range as an input and only considers colinear impacts.
- Accrual of Benefits. One advantage of the BRAKE algorithm is that, unlike the Bendix model, it considers the braking dynamics of each vehicle individually. Moreover, the KRAESP model has the capability to calculate individual numbers of reduced fatalities, reduced

injuries at each AIS severity level and reduced property damage with an unmatched level of accuracy.

- Vehicle Population Trends. The model already includes provisions for forecasting the future vehicle population.
- Crashworthiness Performance. The KRAESP Model was originally developed to study the implementation of advanced crash management systems in the vehicle fleet. It has already been used extensively to study the effects of passive restraints and other systems in the future vehicle fleet.
- False Alarms. The BRAKE algorithm does not address the false alarm problem.
- Anti-skid Braking. Like the Bendix model, the BRAKE algorithm considers the reduced stopping distances provided by anti-skid systems on wet and icy roads but does not consider the benefits of improved vehicle controllability.
- Cost. If used at its maximum level of sophistication, KRAESP would probably be too expensive for this program. However, it allows the user to restrict the scope of investigation as needed.

Conclusions

As we expected, none of the three methodologies could be used intact for an improved cost-benefit analysis of collision avoidance/mitigation systems. However, each contained attributes which proved to be valuable in the subsequent selection of the analytical approach and modifications made.

1.4 RESULTS

Table 1-2 and Figure 1-4 show results obtained in the Bendix Study. Due to our concerns about its methodology and data bases, we feel that caution must be exercised when using the results. A comparative analysis of the different systems indicates that radar accrues substantially greater benefits if it is employed to automatically apply the brakes than if it is simply used as a warning device. The results also indicate that a law of diminishing returns sets in as

TABLE 1-2. RADAR BRAKING SYSTEM CONFIGURATIONS EVALUATED BY THE SENSITIVITY ANALYSIS SIMULATION MODEL

System Number	Radar Range (feet)	Activation Method	Braking Technique	Radar Delay (feet)
1	100	Semi-automatic	Nominal	23
2	100	Semi-automatic	Nominal	11.5
3	100	Semi-automatic	Nominal	0
4	100	Semi-automatic	Anti-lock	23
5	100	Semi-automatic	Anti-lock	11.5
6	100	Semi-automatic	Anti-lock	0
7	100	Automatic	Nominal	23
8	100	Automatic	Nominal	11.5
9	100	Automatic	Nominal	0
10	100	Automatic	Anti-lock	23
11	100	Automatic	Anti-lock	11.5
12	100	Automatic	Anti-lock	0
13	200	Semi-automatic	Nominal	23
14	200	Semi-automatic	Nominal	11.5
15	200	Semi-automatic	Nominal	0
16	200	Semi-automatic	Anti-lock	23
17	200	Semi-automatic	Anti-lock	11.5
18	200	Semi-automatic	Anti-lock	0
19	200	Automatic	Nominal	23
20	200	Automatic	Nominal	11.5
21	200	Automatic	Nominal	0
22	200	Automatic	Anti-lock	23
23	200	Automatic	Anti-lock	11.5
24	200	Automatic	Anti-lock	0
25	300	Semi-automatic	Nominal	23
26	300	Semi-automatic	Nominal	11.5
27	300	Semi-automatic	Nominal	0
28	300	Semi-automatic	Anti-lock	23
29	300	Semi-automatic	Anti-lock	11.5
30	300	Semi-automatic	Anti-lock	0
31	300	Automatic	Nominal	23
32	300	Automatic	Nominal	11.5
33	300	Automatic	Nominal	0
34	300	Automatic	Anti-lock	23
35	300	Automatic	Anti-lock	11.5
36	300	Automatic	Anti-lock	0

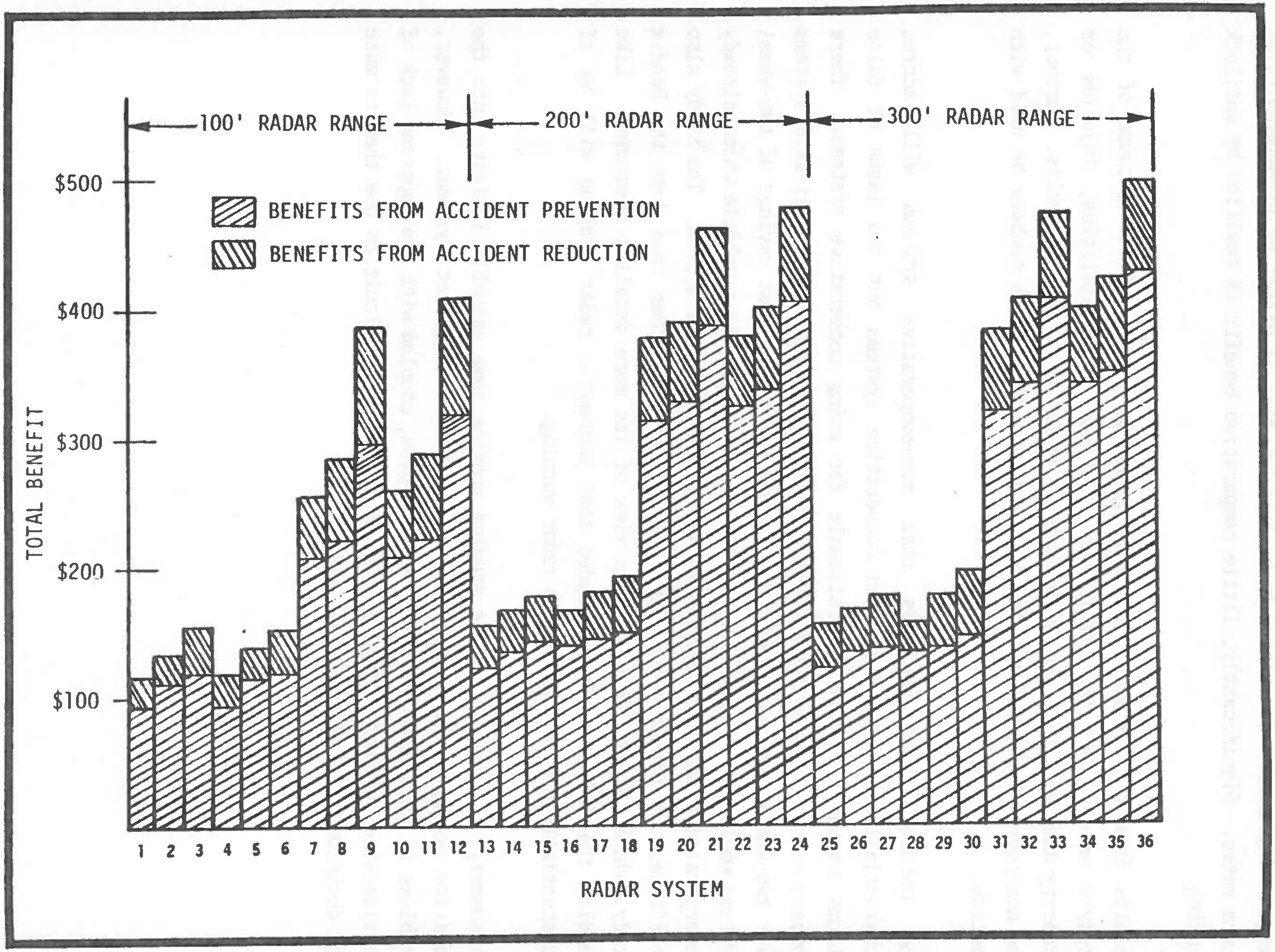

FIGURE 1-4. ESTIMATED TOTAL BENEFIT TO SOCIETY (PER VEHICLE OVER ITS LIFETIME) VS. RADAR SYSTEM CONFIGURATION

range is increased. It remains to be seen how this is offset by increasing false alarm rates. Significantly, little comparative benefit is realized by antilock braking.

Results from the Indiana Study are reproduced in Table 1-3. Because of the study's omission of any benefit calculations (for fatalities, injuries or property damage), it is difficult to draw conclusions from the results. Further, the non-representative data base also requires that these numbers be used with caution.

The Indiana Study concludes that non-cooperative systems will accrue substantially more benefits than cooperative systems but the issue of false alarms remains as a strong rationale for using cooperative systems. There appears to be a strong basis for the selection of four-wheel anti-skid systems over two-wheel systems. The study suggests that the cost savings of two-wheel systems would not justify their selection, especially in a vehicle which already incorporated a radar microprocessor to operate its radar system. The study also attributes considerably more value to anti-skid systems than does the Bendix Study, which is not surprising in view of its more detailed treatment. Like Bendix, the Indiana team concluded that automatic radar braking will be of substantially greater value than radar warning.

In summary, we feel that these studies provide some valuable insights into the relative benefits which could be obtained with different systems. However, problems in their data bases and methodologies, coupled with the apparent lack of consideration given to false alarms, make it very difficult to use them to make any decisions on a benefit/cost basis.

TABLE 1-3. SUMMARY OF EFFECTIVENESS OF BRAKING SYSTEM MODELS (TOTAL N - 215)

	Certain		Certain or Probable		Certain, Probable or Possible	
	Accidents Prevented	Prevented or Reduced in Severity*	Accidents Prevented	Prevented or Reduced in Severity*	Accidents Prevented	Prevented or Reduced in Severity*
Models	Percent	Percent	Percent	Percent	Percent	Percent
1. Radar Warning — Cooperative	0.5	5.1	6.0	12.1	14.9	14.9
2. Radar Warning — Noncooperative	0.5	6.5	9.3	16.7	21.9	21.9
3. Rear Wheel Anti-Lock	0.5	0.5	1.9	1.9	3.7	3.7
4. Four-Wheel Anti-Lock	2.8	3.7	7.9	7.9	13.0	13.0
5. Cooperative Warning & Rear Wheel Anti-Lock	0.9	5.6	7.9	14.0	18.1	18.1
6. Noncooperative Warning & Rear Wheel Anti-Lock	0.9	7.0	11.2	18.6	25.1	25.1

*Severity Reduction was defined as occurring when impact speed of any one vehicle was reduced 10 mph or 25 percent, whichever was greater.

TABLE 1-3. (CONT'D)

Models	Certain		Certain or Probable		Certain, Probable or Possible	
	Accidents Prevented	Prevented or Reduced in Severity*	Accidents Prevented	Prevented or Reduced in Severity*	Accidents Prevented	Prevented or Reduced in Severity*
	Percent	Percent	Percent	Percent	Percent	Percent
7. Cooperative Warning & Four-Wheel Anti-Lock	4.2	9.3	13.5	16.7	23.7	23.7
8. Noncooperative Warning & Four-Wheel Anti-Lock	4.7	11.2	16.7	21.9	30.2	30.2
9. Cooperative Warning & Actuation & Rear Wheel Anti-Lock	13.0	15.8	20.0	21.4	25.6	26.0
10. Noncooperative Warning & Actuation & Four-Wheel Anti-Lock	18.1	25.1	31.6	38.1	41.9	45.1

*Severity Reduction was defined as occurring when impact speed of any one vehicle was reduced 10 mph or 25 percent, whichever was greater.

SECTION 2
SELECTION OF ACCIDENT DATA BASE AND ANALYSIS APPROACH

2.1 INTRODUCTION

This section documents the results of the Task 2 effort of this program. The efforts included:

- Review of available accident data bases; and
- Review of candidate analytical approaches.

The available accident data bases were reviewed using the criteria that were generated as a result of the Task 1 Methodology Review (Ref. 7). The results are presented in Section 2.2.

The candidate accident analysis approaches were also reviewed using the criteria generated in the Task 1 analysis and presented in Section 1. The results are presented in Section 2.3. Section 2.3 also identifies the modifications required for each methodology.

Section 2.4 presents a relative comparison of the candidate approaches based on a series of selection criteria, and concludes with a preferred accident analysis approach and a data set that was subsequently used on this program.

2.2 REVIEW OF AVAILABLE ACCIDENT DATA BASES

In the methodology review (Ref. 1), we specified three criteria for our study's data base:

- It must be nationally representative;
- It must include information that adequately describes the pre-impact environment — vehicle traveling and impact velocities, direction and area of impact, presence or absence of braking, etc.; and

- It must include measures that will facilitate accurate estimations of societal losses.

We identified four data sources which could be employed in our analysis. Their applicability toward the above criteria is summarized below.

The Multidisciplinary Accident Investigation (MDAI) File, begun in 1969, contains data compiled by experts that describe virtually all of the pertinent accident characterisitcs (including the pre-impact environment and societal consequences) in considerable detail. However, it is not at all representative of the current accident environment. First, it was constructed with an intentional bias toward severe accidents. Second, its data was obtained in the early seventies which means that it is descriptive of older cars traveling at higher speeds (i.e., before the 55 mph speed limit). Finally, there are geographical biases (urban vs. rural) in sampling that also detract from the MDAI File's national representativeness.

The National Crash Severity Study (NCSS) File is much more recent (circa 1978) and is considerably more representative of the national experience. The NCSS File contains samplings of towaway accidents from various parts of the country. The fact that non-towaway accidents are not included biases NCSS data toward severe accidents, although to a lesser degree than is found in MDAI data. Unfortuantely, the NCSS data do not include adequate pre-impact information for our accident reconstruction step, and thus can only be used in conjunction with another data source.

North Carolina, Pennsylvania and Texas state files all contain relatively recent data (from 1977 to present) based on statewide police-reported accidents. Except for the Texas file which does not include traveling speeds, all three files contain enough data to describe most, if not all, of the pre-impact environment. Our main concern with using state files, of course, is that they are not nationally representative. By using data from more than one state, we can alleviate this problem to some extent.

The National Accident Samplng System (NASS) was designed to become the first continuous and truly representative sampling of the national accident environment. The NASS data are compiled by teams of specially trained technicians and, while they are not quite as thorough as data from the MDAI File, they include all of the necessary information for a collision avoidance study with our intended scope. Moreover, the fact that it is a continuous sampling system means that the data are current and that the results of analyses using it can readily be compared to future work.

Since the accidents to be investigated are selected from police reports, the NASS System contains non-towaway accidents and does not have the biases toward severe accidents evident in MDAI and NCSS data. (Still, a residual bias remains because unreported accidents are not included.) Significantly, NASS data are collected in randomly chosen geographical areas rather than in areas where data collection would be easiest or least expensive. Commenting on the NASS's efforts to remove biases in data collection, the NHTSA reported that the fully-implemented system should reduce sampling errors in nationally compiled statistics by as much as an order of magnitude compared to statistics obtained from MDAI and NCSS data (Ref. 8).

For the above reasons, the National Accident Sampling System File was our preferred choice of a data base with which to study collision avoidance systems. Problems exist, however, with one of its more desirable qualities – its newness. Our experience with other data files such as the NCSS suggests that data obtained in the first year of collection is often difficult to use. At the time, only first year NASS data were available for use. Furthermore, the critical pre-impact data were not yet automated and could not be used in a computerized analysis on this program.

The problems with the NASS File would be least troublesome in a hard-copy analysis such as the Indiana methodology. Therefore, we decided that NASS data would be used with the Indiana methodology and expected that enough information existed in the file to allow us to draw meaningful conclusions.

If one used one of the computerized methodologies (Bendix or KRAESP/BRAKE), it would be necessary to use either NCSS or NASS data for at least part of the analysis. Of critical importance are the relative velocity (Vrel) distributions which help determine the ratios of low and high severity accidents. If MDAI or state data are used, their Vrel distributions would have to be adjusted to match the distributions found in NCSS or NASS data, since the latter two provide the only distributions that are representative on a national scale.

In summary, we elected to use the NASS File exclusively for our evaluation of collision avoidance systems. If that proved impractical, then we opted to use MDAI or State Files where it was necessary (such as in the accident reconstruction step) and still use either NCSS or NASS data to help insure national representativeness.

Appendix B contains record layouts and coding information for the four data bases discussed in this section. Table 2-1 summarizes the comparative evaluation of the four data files. As mentioned earlier, even with qualitative evaluation measures of "poor," "good" and "very good," the NASS data file stands out as the preferred data file.

Following the initial selection of the NASS data as the prime candidate, the data file was analyzed for its content and quality. The analysis revealed that:

1. The critical data variable Delta-V was missing in a large number of cases making NASS data unacceptable for use.
2. The NASS data file does not have pre-crash information coded on the computer. The lack of pre-crash information made the NASS file further unacceptable.

Quantitative results of the analysis to determine the availability of Delta-V in the NASS data file are shown in Appendix C.

As an alternative, State of North Carolina accident data for 1979 was selected and used as the data base. Preliminary analysis of the data base for reasonableness and completeness indicated that all critical data items were usable for the analysis.

Comparison of the North Carolina and the national data indicated that motor vehicle accidents in North Carolina occurred more frequently in rural locations

TABLE 2-1. COMPARATIVE EVALUATION OF THE FOUR DATA BASES

Is the data base nationally representative?

MDAI	No; Poor*
NCSS	Yes; Good
State Files	No; Poor
NASS	Yes; Very Good

Are the pre-impact environment data adequate?

MDAI	Very good
NCSS	Poor
State Files	Fair
NASS	Very good

How well does it represent the current accident picture?

MDAI	Poor*
NCSS	Good
State Files	Good
NASS	Very good

Remarks

MDAI
- Relatively old data file.
- Represents relatively old traffic and accident environment.
- Contains geographical biases.

NCSS
- Represents relatively recent traffic and accident environment.
- Pre-impact environment data inadequate.
- Biases toward severe accidents.

State Files
- Most pre-impact information available.
- Not nationally representative.
- If more than one state file is used, data categories may have to be recoded before merging the files.

NASS
- File relatively new.
- Does not have pre-impact factors coded on computer.

*Can be modified to be more representative.

and at higher speeds, involved a lower frequency of icy road and snow conditions, and involved slightly older vehicles. A simple adjustment procedure was then implemented for the 1979 North Carolina data file. This adjustment involved the use of statistical case weights to reproduce the same distribution over the speed limits in North Carolina as is found in the NASS. The details of this adjustment are included in Appendix D.

2.3 REVIEW OF ACCIDENT ANALYSIS APPROACHES

Although the Bendix, Indiana and Kinetic Research methodologies are dissimilar in many respects, each of them performs the four basic steps (labelled A, B, C, and D) shown in Figure 2-1.* The methodology that we eventually selected for this analysis would also perform these steps and would probably resemble the generalized methodology shown here. Therefore, to better determine the suitability of each approach for the proposed analysis, we identified the modifications required for each methodology to adequately perform each step.

The Four Basic Steps

The function and purpose of each step are briefly summarized below:

Accident Selection (Step A). The present approaches all operate by selecting accidents from a data base for individual examination. The Kinetic Research and Indiana techniques select directly from the data base, while the Bendix technique generates an accident at random from probability distributions derived from the data base. Both approaches are valid and will generate identical results provided that the sample sizes are sufficiently large.

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*The Kinetic Research methodology is more sophisticated and constructs a relative velocity (Vrel) distribution for each system after reconstructing all of the accidents. It then performs cost calculations on the basis of the Vrel distributions.

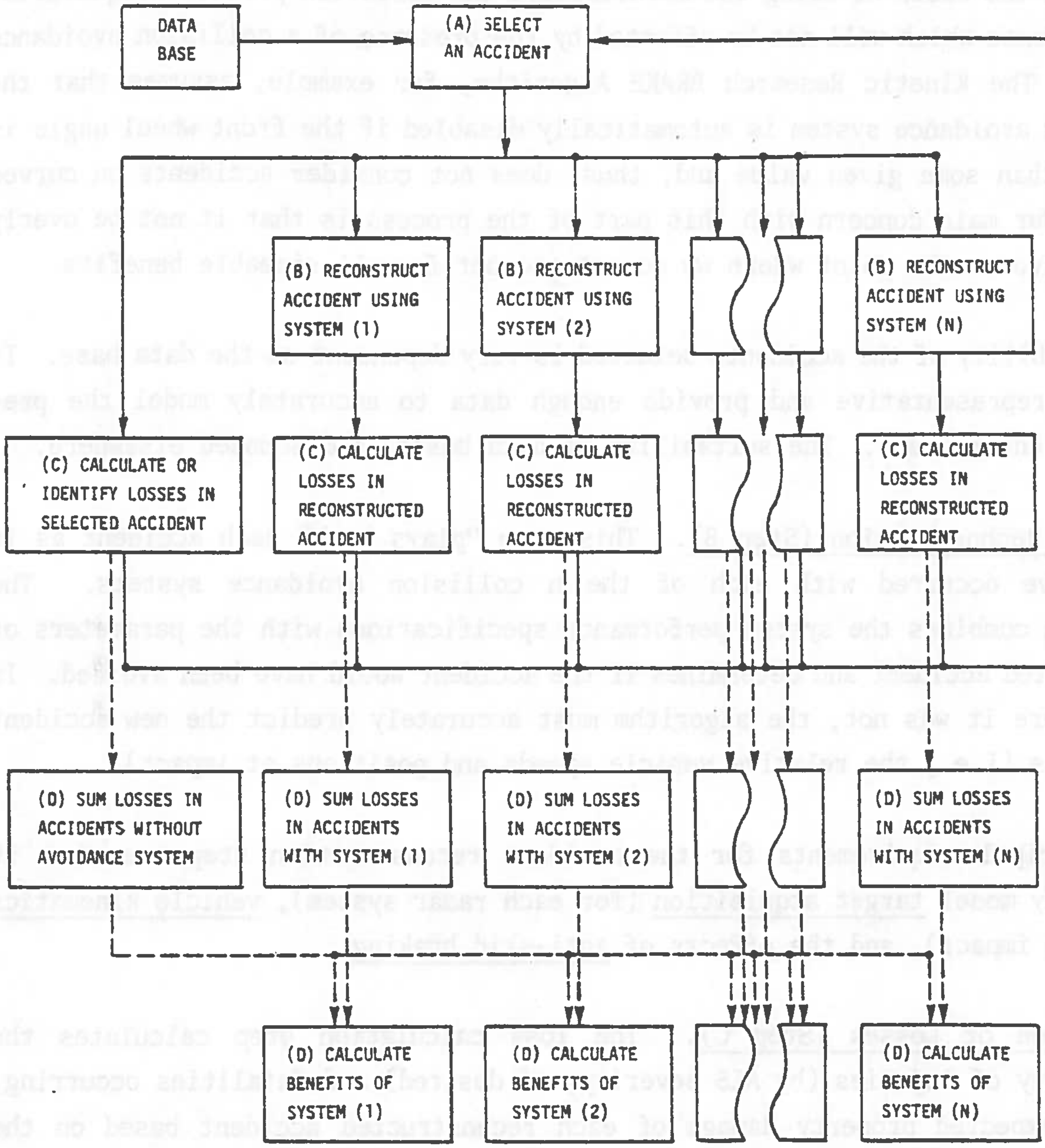

FIGURE 2-1. GENERALIZED METHODOLOGY FOR CALCULATING THE BENEFITS OF N ACCIDENT AVOIDANCE SYSTEMS

Note: The methodology performs the B and C steps for all N systems before returning to Step A. All D steps are only performed once.

To reduce the costs of using the methodology, the selection process disqualifies any accidents which will not be affected by the presence of a collision avoidance system. The Kinetic Research BRAKE Algorithm, for example, assumes that the collision avoidance system is automatically disabled if the front wheel angle is greater than some given value and, thus, does not consider accidents on curved roads. Our main concern with this part of the process is that it not be overly restrictive to the point where we do not account for all sizeable benefits.

The suitability of the accidents selected is very dependent on the data base. It must be representative and provide enough data to accurately model the pre-accident environment. The suitability of data bases is discussed elsewhere.

Accident Reconstruction (Step B). This step "plays back" each accident as it would have occurred with each of the n collision avoidance systems. The algorithm combines the system performance specifications with the parameters of the selected accident and determines if the accident would have been avoided. In cases where it was not, the algorithm must accurately predict the new accident kinematics (i.e., the relative vehicle speeds and positions at impact).

Our principal requirements for the accident reconstruction step are that it accurately model target acquisition (for each radar system), vehicle kinematics (prior to impact), and the effects of anti-skid braking.

Calculation of Losses (Step C). The loss calculation step calculates the probability of injuries (by AIS severity, if desired) and fatalities occurring, and the expected property damage of each reconstructed accident based on the relative vehicle velocities calculated in Step B. It also calculates the losses in the selected accident as it would have occurred without the presence of a collision avoidance system. (This last calculation is only necessary for methodologies like the Bendix Model which generate accidents. If the selected accident was sampled directly from the data base, then we can simply use the losses which actually occurred.)

The cost calculation algorithm must be able to model the effects of vehicle size and vehicle crashworthiness.

Benefit Calculation (Step D). The benefit calculation step sums the total losses for all accidents with each system and for the case of no system. The total benefit of any system is simply the difference of these sums.

Bendix Model

The Bendix Model's accident selection methodology (Step A) is not overly restrictive and could effectively be employed for the accident selection/generation task. However, it will have to be modified if another data base is utilized.

The following modifications are required to make the model suitable for the accident reconstruction task (Step B):

- The target acquisition methodology adequately accounts for the effects of range and target size but should be expanded to include beamwidth effects as well. (By studying the effects of changing beamwidth, we can begin to evaluate the trade-offs between missed targets and false alarms.) Other minor changes may be required.

- The Bendix treatment of vehicle kinematics in head-on collisions is inaccurate as we noted in the methodology review. Furthermore, it does not have the capability to model head-on accidents where only one vehicle has a radar braking system. Therefore, the algorithm which reconstructs head-on collisions will have to be rewritten. At this time, we don't see any reason to change the simulation of side and rear impacts but may develop a more comprehensive treatment if the data base permits.

- The Bendix methodology will have to be expanded so that it can evaluate various control laws.

- Finally, the Bendix Model will have to be upgraded to consider the improved controllability of anti-skid braking.

The following modifications are required to upgrade the Bendix calculation algorithm (Step C):

- The model's estimation of injuries, fatalities and property damage based on traveling speeds is seriously flawed as we noted in the methodology review, and will have to be totally revised.

- A provision is required to account for vehicle size differences, including future changes in the vehicle mix.

- A provision is required to account for changes in vehicle crashworthiness. The entire Bendix loss calculation methodology, in effect, will have to be written.

Indiana Study

When selecting accidents, the Indiana team did not include any which included large trucks, pedestrians or bicyclists. As Bendix noted, it is possible to detect the latter two targets in time to apply radar brakes, and the outright exclusion of accidents including them should be reassessed. Similarly, we do not see any reason to exclude collisions with large trucks (which have very large radar cross-sections).

The Indiana methodology for reconstructing accidents is inherently a hard-copy review in contrast to a computerized algorithm like the Bendix Model. Thus, it is impossible to review their technique in great detail since it was not fully documented. Nevertheless, we will probably want to add some sort of detection probability function to the target acquisition methodology which now facilitates a comprehensive study of such parameters as beamwidth, curved roads, etc., but still does not consider the possibility of having a target within range and failing to detect it (as Bendix does).

The Indiana methodology only takes a cursory look at calculating accident losses and is, therefore, inappropriate for use in Step C.

Kinetic Research Methodology

The Kinetic Research BRAKE Algorithm only evaluates colinear vehicle-to-vehicle and vehicle-to-fixed object collisions on straight roads. This is probably too restrictive and will have to be expanded.

The following modifications are required to perform the accident reconstruction step:

- A more sophisticated target acquisition methodology is required; at present, the BRAKE algorithm simply assumes that targets are detected when they come within range.

- A more sophisticated treatment of vehicle kinematics will be required if we decide to analyze non-colinear impacts.

- The BRAKE algorithm requires a provision to study the effects of improved controllability of anti-skid braking.

The Kinetic Research KRAESP Model can perform the loss calculation step with little or no modification.

This summarizes the modifications required for each methodology to perform each step. We emphasize that the above discussion only considers benefits, and not costs. One cost is due to false alarms but, since none of the methodologies even consider it, we have not included this subject in the above discussion.

2.4 COMPARATIVE EVALUATION OF CANDIDATE ANALYSIS APPROACHES

As mentioned in Section 2.3, there are three basic analytical approaches that are available for this project. They are the Bendix, Indiana, and in-house KRAESP methodologies.

A preliminary review had indicated that none of these three systems could be used directly in the form in which it existed in order to meet the goals and objectives of this project. A series of selection criteria was developed and used to make a selection of a preferred approach that was recommended for use on this project. The candidate approaches that were evaluated included the three basic methodologies identified above as well as consideration of four other approaches.

Selection Criteria

The selection criteria that were used are listed in Table 2-2 and presented in four separate groups. The first three groups correspond to Steps A, B, C and D of the basic methodologies as identified in Section 2.3. The fourth group includes six criteria which were applicable to the overall aspects of an approach used on this project, and are termed "General Considerations."

Candidate Approaches

The three basic candidate approaches are:

1. Bendix;
2. Indiana; and
3. KRAESP.

Additionally, the four other approaches which were considered are:

4. The Bendix methodology for Step A and modified KRAESP for Steps B, C, and D;
5. The Bendix methodology for Step A, the modified Bendix methodology for Step B, and KRAESP for Steps C and D;
6. State files like North Carolina to get Vrel distributions which will be corrected using NASS files for Step A, and Steps B, C, and D will be done using modified KRAESP; and
7. Two approaches simultaneously for Step A. One will be the Bendix methodology and the second will be the use of an actual data file to obtain nationally representative Vrel distributions. These two will

TABLE 2-2. SELECTION CRITERIA

1.	<u>Accident Selection (Step A)</u>
1.1	Representativeness of Vrel distributions.
1.2	Versatility in the sense that can be applied unchanged with another data base or a combination of data bases.
1.3	Depth of data base needed to obtain representative accident selection.
1.4	Size of data base needed to obtain the representative Vrel distribution.
2.	<u>Accident Reconstruction Using Selected System (Step B)</u>
2.1	Accuracy of target acquisition methodology.
2.2	Level of sophistication in use of specified CMS algorithm.
2.3	Ability to identify skidding cases and to assess the improved controllability of a vehicle with antiskid brakes.
2.4	Treatment of weather and road effects.
2.5	Ability to accommodate cases in which both vehicles do not have CMS.
2.6	Ability to accurately model the accident environment.
3.	<u>Calculation of Accident Consequences (Step C)</u> <u>and Calculation of Benefits (Step D)</u>
3.1	Ability to handle new vehicle system effects (e.g., automatic restraints and improved bumpers).
3.2	Ability to account for changes in the future vehicle population.
3.3	Treatment of false alarms.
3.4	Ability to assess phase-in effects.
3.5	Ability to handle vehicle class effects.
3.6	Ability to handle lifetime quantification of benefits.
3.7	Accuracy of estimations of injuries, fatalities and property damage.
3.8	Accuracy of calculation of benefits.

TABLE 2-2. (CONT'D)

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4. <u>General Considerations</u>

4.1 Level of modifications necessary.

4.2 Cost of modifications.

4.3 Availability of documentation.

4.4 Cost of running the program.

4.5 Familiarity with the program.

4.6 Compatibility with selected data bases.

---

be compared and analyzed, and adjustments will be made as necessary. Then, Steps B, C, and D will be handled using the KRAESP approach. Additionally, the Indiana approach will be used for a selected number of hard-copy cases.

Scrutiny of the above four approaches shows that they are generated to take advantage of good attributes of the first three basic methodologies. For example, Task 1 and 2 efforts clearly indicated that the Bendix approach has a good basic Step A technique. Step B efforts do require modifications to both the Bendix and KRAESP approaches. Steps C and D are handled more effectively by KRAESP than they are with the Bendix approach. Hence, modifications to KRAESP are much less than those required for the Bendix approach.

Results of a comparative evaluation of the seven approaches are shown in Table 2-3. The seven candidate approaches are numbered 1 to 7 in the table, and they correspond with the seven approaches listed earlier. The evaluation criteria are numbered in the table the same way as they are listed in Table 2-2.

A qualitative evaluation of the seven candidate methodologies based on three scoring ranges of "poor," "good" and "very good" confirms our initial findings that the Bendix approach has its primary strengths in Steps A and B, and KRAESP has its strengths in Steps B, C, and D. Hence, the combinations that are considered clearly show that candidate approach number 7 is the preferred approach for this project.

The differences shown by the qualitative evaluation are so obvious that approaches 6 and 7 appear to be well ahead of the other five which were considered. Addition of limited hard-copy analysis in approach 7 makes it the preferred approach over approach 6 and, hence, was recommended for this project.

TABLE 2-3. COMPARATIVE EVALUATION OF CANDIDATE APPROACHES

	Basic Approaches			Approach Combinations			
	Bendix 1	Indiana 2	KRAESP 3	4	5	6	7
	Selection Criterion 1.* Accident Selection (Step A)						
1.1	Very good with proper data file	Very large number needed	Very good with proper data file	Very good with proper data file	Very good with proper data file	Dependent on state data	Very good
1.2	Yes; Very good	Yes; Very good, but not cost and time effective	Yes; Very good	Yes; Very good	Very good	Poor	Very good
1.3	Very good with large data file	Poor	Good	Very good with large data file	Very good with large data file	Very good with large data file	Very good with large data file
1.4	Large	Large	Large	Large	Large	Large	Large
	Selection Criterion 2.* Accident Reconstruction (Step B)						
2.1	Good	Subjective	Good	Very good	Very good	Very good	Very good
2.2	Good	Subjective	Good	Very good	Very good	Very good	Very good
2.3	Poor	Subjective	Poor	Very good	Very good	Very good	Very good
2.4	Good	Subjective	Good	Very good	Very good	Very good	Very good
2.5	Poor	Subjective	Poor	Very good	Very good	Very good	Very good
2.6	Good	Subjective	Very good	Very good	Very good	Very good	Very good

*See Table 2-2 for definition of the Selection Criteria.

TABLE 2-3 (continued)

	Basic Approaches			Approach Combinations			
	Bendix 1	Indiana 2	KRAESP 3	4	5	6	7
	Selection Criterion 3.* Calculation of Accident Consequences (Step C) and Calculation of Benefits (Step D)						
3.1	Poor	Subjective	Very good	Very good	Good	Very good	Very good
3.2	Poor	Subjective	Very good	Very good	Good	Very good	Very good
3.3	Good	Subjective	Good	Very good	Good	Very good	Very good
3.4	Poor	Subjective	Very good	Very good	Good	Very good	Very good
3.5	Poor	Subjective	Very good	Very good	Good	Very good	Very good
3.6	Poor	Subjective	Very good	Very good	Good	Very good	Very good
3.7	Good	Subjective	Very good	Very good	Good	Very good	Very good
3.8	Good	Subjective	Very good	Very good	Good	Very good	Very good
	General Considerations						
4.1	Extensive Poor	Subjective	Good	Very good	Good	Very good	Very good
4.2	Poor	Subjective	Good	Very good	Good	Very good	Very good
4.3	Good	Subjective	Very good	Very good	Good	Very good	Very good
4.4	Good	Subjective	Very good	Very good	Good	Very good	Very good
4.5	Good	Subjective	Very good	Very good	Good	Very good	Very good
4.6	Good	Subjective	Very good	Very good	Good	Very good	Very good

*See Table 2-2 for definition of the Selection Criteria.

SECTION 3
RADAR SYSTEM PERFORMANCE STUDY

3.1 INTRODUCTION

This section documents the results of the radar system performance study. The system description was obtained by requesting the information directly from the developers of the known system. Additionally, two overseas trips were made – one to Japan and the other to Germany – to visit developers of the radar systems in those two countries. The collected data and information are presented in Section 3.2, Review of Available Systems and in Appendix E, Trip Reports.

The specifications and the performance data on the reviewed systems are presented in Section 3.3. The system specification and performance revealed that a key parameter for the benefit evaluation of a system is its control logic. The reviewed systems were grouped together under three levels of sophistication. The rationale behind the grouping and the groups themselves are shown in Section 3.4. The system cost/performance relationship and the life cycle costs are discussed in Section 3.5. Analytical computer models were developed and exercised to evaluate the system performance. The developed models and the system performance evaluation results are summarized in Section 3.6. More detailed descriptions of the models and performance analysis are presented in Appendices F and G.

3.2 REVIEW OF AVAILABLE SYSTEMS

A literature search at the beginning of this program identified 10 radar collision avoidance systems which were either functional or under development. The basic characteristics of the ten systems are summarized in Table 3-1.

These can be separated into three basic types of systems: pulsed, FM-CW, and DIPLEX. The range of the return signal is from about 5m to about 125m with an accuracy of about one meter. The overall sensitivity (i.e., the ratio of received power to transmitted power) is difficult to evaluate for the different systems. For comparison, it will be necessary to develop some normalization for

TABLE 3-1. RADAR COLLISION AVOIDANCE SYSTEMS

Description	Nissan-Mitsubishi	Benz-SEL
System		
Principle	Pulse doppler	FM-CW
Range	5 to 127 m	10 to 100 m
Accuracy	1 m	± 2.5 m
Relative speed	± 1 to ± 127 km/h	-30 to 160 km/h
Accuracy	1 km/h	± 2.5 km/h
Sensitivity - Pr/Pt	-78 dB	
Antenna		
Number and type	1 parabola	2 parabola
Beamwidth	$H3.4^{o}$, $V6^{o}$	$H2.5^{o}$, $V4^{o}$
Polarization	45^{o}	V
Tx & Rx		
Main oscillator	Gunn	Gunn
Frequency	24.15 GHz	35 GHz
Output power	20 mW	
Pulse width	20 ns	CW
Receiver	Homodyne	Superheterodyne
Logics		
Microcomputer	8080A	
Cycle time	22.5 ms	60 ms
Main logic*	$R > R^2/2$	$R > \frac{V_1^2}{2\alpha_1} - \frac{V_2^2}{2\alpha_2} + V_1 T + S$
Range cut by steering angles	Contained in program .	Contained
Notes		
Supported by	MITI	Benz-SEL plus Government
Started in	1974	1975

* V_1 = vehicle speed; V_2 = target speed; T = delay time

TABLE 3-1. (CONT'D)

Description	Bosch-Telefunken	BMW-VDO
<u>System</u>		
Principle	Pulse	Pulse
Range	5 to 120 m	5 to 120 m
Accuracy	+ 1 m	± 1 m
Relative speed	150 km/h	130 km/h
Accuracy	± 3.6 km/h	
Sensitivity - Pr/Pt		
<u>Antenna</u>		
Number and type	2 parabola	2 parabola
Beamwidth	H2.5°, V4°	H2.5°, V4°
Polarization	V	V
<u>Tx & Rx</u>		
Main oscillator	Gunn	Gunn
Frequency	35.6 GHz	35 Ghz
Output power	300 mW	200 mW
Pulse width	20 ns	30 ns
Receiver	Superheterodyne	Superheterodyne 250 kHz PRF 1.5 mW average
<u>Logics</u>		
Microcomputer		
Cycle time	100 to 200 ms	280 ms
Main logic*	$R > \frac{V_1^2}{2\alpha_1} - \frac{V_2^2}{2\alpha_2} + V_1T$	$R > \frac{V_1^2}{2\alpha_1} - \frac{V_2^2}{2\alpha_2} + V_1T$
Range cut by steering angles	Contained	Contained
<u>Notes</u>		
Supported by	Bosch-Telefunken plus Government	BMW-VDO plus Government
Started in	1975	1968

* V_1 = vehicle speed; V_2 = target speed; T = delay time

TABLE 3-1. (CONT'D)

Description	Bendix	CA Research	RCA
<u>System</u>			
Principle	Diplex	Pulse, gated	FM-CW
Range	30 to 75 m	6 to 96 m	6 to 30 m
Accuracy			0.2 m
Relative speed			0 to 60 km/h
Accuracy			2.5 km/h
Sensitivity - Pr/Pt			
<u>Antenna</u>			
Number and type	1 parabola		2 printed
Beamwidth	H2.5°, V4°	H10°	H3°, V5°
Polarization	45°	45°	45°
<u>Tx & Rx</u>			
Main oscillator	Gunn	Gunn	Gunn
Frequency	36 GHz ± 410 kHz	24 GHz	17.5 GHz
Output power	25 mW	100 mW to 2.5 W	20 mW
Pulse width	730 ns	25 ns	
Receiver	Homodyne		Homodyne
<u>Logics</u>			
Microcomputer			1802
Cycle time			80 ms
Main logic*	$R - 2\dot{R} < 0$		$K_1V_1 + K_2R + K_3R < 0$
Range cut by steering angles	Contained		Contained
<u>Notes</u>			
Supported by	(Independent)	(Independent)	(Independent)
Started in			1971

* V_1 = vehicle speed; V_2 = target speed; T = delay time

TABLE 3-1. (CONT'D)

Description	Sperry	British	Rashid
<u>System</u>			
Principle	Baseband	FM-CW	
Range	45 m	Sawtooth Pulse	
Accuracy	0.1 m	period	
Relative speed			
Accuracy			
Sensitivity - Pr/Pt			
<u>Antenna</u>			
Number and type	3 dipole	2 parabola	1 parabola
Beamwidth	H2.5^{o}		
Polarization	?		
<u>Tx & Rx</u>			
Main oscillator	Differentiating antenna Base-band radiation	Gunn	X-band
Frequency	--	31.8 to 33.4 GHz Sweep of 0.25 GHz	--
Output power	--	--	--
Pulse width	--	15 ms	--
Receiver	Super-regenerative receiver	--	--
<u>Logics</u>			
Microcomputer			
Cycle time			
Main logic			
Range cut by steering angles			
<u>Notes</u>			
Supported by	DOT	Lucas	(Independent)
Started in	1974		

a standard target such as an automobile. Thus, with transmitted power and sensitivity, the received power can be determined for each system for a known cross-section.

The antenna is typically parabolic with the beamwidth between 2 and 3 degrees in the horizontal direction and between 4 and 6 degrees in the vertical direction. The polarization is linear, either vertical or at 45 degrees from the vertical.

The primary transmitter used is a Gunn oscillator with 10s-of-Megawatt power. The frequency ranges from 10 to 35 GHz, with higher frequencies being more common.

The signal processing that is used is a key parameter and is earmarked for more investigation. It is also perhaps the area of most rapid possible development. Some of the radar systems are microprocessor controlled and operated; the signal processing can calculate range and vehicle speed and it also does some target discrimination.

The 16 individuals and companies listed in Table 3-2 were contacted with requests for specific radar system data and performance characteristics.

The data requested from these sources were:

1. Transmitter (power, frequency, pulse width, etc.);
2. Receiver (sensitivity, range, accuracy);
3. Antenna (type, number, beamwidth, both horizontal and vertical);
4. System Analysis (microprocessor used, parameters calculated); and
5. System Performance (test sconducted and principal results).

The responses received consisted of published papers, descriptive brochures, and other non-proprietary information. Two companies, TRW, Inc. and Ford Motor Company, indicated that they were currently inactive in this general area. Other companies like Rashid and General Motors did not want to release information on their in-house projects. In general, it can be said that the data received as a result of the letter request did not add substantially to what we had already available.

TABLE 3-2. INDIVIDUALS AND COMPANIES CONTACTED FOR SPECIFIC RADAR SYSTEM DATA AND PERFORMANCE CHARACTERISTICS

1. Mr. Jerry Rivard, Chief Engineer
   Ford Motor Company
   21500 Oakwood Boulevard
   P.O. Box 2053
   Dearborn, MI 48121

2. Dr. Neal Richardson
   Director, Advanced Sysems Engineering
   Automotive Worldwide-TRW, Inc.
   Mail Station E-1/9062
   One Space Park
   Redondo Beach, CA 90278

3. Mr. Trevor O. Jones
   Vice President
   Automotive Worldwide-TRW, Inc.
   30,000 Aurora Road
   Cleveland, OH 44139

4. Mr. George Rashid
   Vehicle Safety Radar Systems, Inc.
   35477 S. Gratist
   Mt. Clemens, MI 48043

5. Dr. Erwin Belohoubek
   RCA Corporation
   David Sarnoff Research Center
   Princeton, NJ 08540

6. Mr. Snelling R. Brainard
   175 Spring Street
   The Jonathan Gibbs House
   Newport, RI 08240

7. Dr. Dietmar zur Heiden
   Standard Elektrik Lorenz AG
   Hellmuth-Hirth-Strasse 42
   7000 Stuttgar 40
   West Germany

8. Dr. F. Ackermann
   Abstandswarnsysteme, Radar
   Robert Bosch Gmb 4
   Stuttgart
   West Germany

9. Abstandswarnsystem, Radar
   AEG-Telefunken, Ulm
   West Germany

10. Abstandswarnsysteme, Radar
    VDO Adolf Schindling AG
    Sodener Strasse 9
    6231 Schwalbach (TS)
    West Germany

11. Dr. Werner Fogy
    DFVLR
    Oberpfaffenhofen
    9031 Wessling
    West Germany

12. Dr. J.B. Bidwell
    Executive Director
    General Motors Research Lab
    Warren, MI 48090

13. Dr. Louis Nagy
    General Motors Research Lab
    Warren, MI 48090

14. Dr. Gerald F. Ross
    Sperry Research Center
    Sudbury, MA 01776

15. Mr. Takayuki Makino
    Toyota Motor Company, Ltd.
    One, Toyota-cho, Toyota City
    Aichi Pref., 471
    Japan

16. Mr. Yukitsugu Hirota
    Nissan Motor Company, Ltd.
    560 Sylvan Avenue
    Englewood Cliffs, NJ 07632

On the basis of information received (or lack thereof), the scheduled trips to Japan and Germany became more important. The places visited were Toyota and Nissan in Japan, and VDO Adolf Schindling AG, the Institute fur Verkehrswesen at the University of Karlsruhe, Standard Electrik Lorenz AG (SEL), and Robert Bosch GMBH in Germany.

The objective of the overseas trips was to obtain more details on the systems and, specifically, to obtain more performance and test data. Some of the specific areas where more information was sought are listed below:

1. Front end. What type of antenna is used? If a parabolic dish, what is the focal distance, the length and width, and the tolerances? If the feed is a horn, what type of flare, what type of guide, and what is the mode of excitation? Patterns would be helpful.

2. System Characteristics. What is the source, the power supply, the anticipated output power and system gain? What modulation, polarization, and detection techniques? How is the signal amplified, and what type of filtering? How is frequency stability maintained, and to what tolerance? How is cross-talk to be avoided?

3. Signal processing. What microprocessor is used, and how is it programmed? How do they read out closing speed, range, ground speed, and road conditions? Under what driving conditions is the set operational? How do they take into account the multiple target problem? Do they observe length of returns, magnitude, above a threshold, is there a time delay (integration), and if so, what is it?

4. Activation and warning. What is done with the output signals and why? What have been observed results?

5. Test Data. False alarm rate, pedestrian detection, and influence of environmental factors.

6. Cost. Developmental costs, manufacturing cost, cost to consumers, and maintenance cost.

7. Schedule. Development schedule and future plans.

The information received from Japan and Germany is summarized in the trip reports in Appendix E.

3.3 SYSTEM SPECIFICATIONS AND PERFORMANCE

3.3.1 System Specifications

The updated system specifications and performance rating are shown in the descriptions that follow.

- Bendix System – AN FM-CW Set

Range	30 - 75m
Relative Speed	--
Response Time	100 ms
Transmitted Frequency	
Local Oscillator	
IF	
Peak Power Output	20mW
Average Power Output	
Pulse Width	20ns
PRF	

Range Algorithm:

$$R - 2\dot{R} < 0$$

Sophistication:	Level I

- Robert Bosch GmbH, Stuttgart AEG-Telefunken, Ulm – Bistatic, Pulsed Set (Figure 3-1)

Range	5 to 120 m $\pm$ 1
Relative speed	0 to + 150 km/h

FIGURE 3-1. BOSCH RADAR SYSTEM

Response time	300 ms
Transmitted frequency	35.6 GHz
Local oscillator	
IF	
Peak power output	300 mW
Average power output	1.5 MW
Pulse width	20 ns
PRF	250 kHz

Range algorithm:

$$S_a = \frac{V_2^{\ 2}}{2b_2} - \frac{V_2^{\ 2}}{2b_1} + T V_2$$

Sophistication:	Level II

- Fujitsu Ten, Ltd, and Toyota Motor Co., Ltd.
  – An FM-CW set

Range	--
Range resolution	--
Relative speed	--
Response time	--
Transmitted frequency	50 GHz
Modulation frequency	--
Frequency deviation	--
Antenna	--
Power output	30 mW
Range Algorithm:	Not known
Sophistication:	May be Level II+

The Fujitsu-Toyota radar system is an advanced, sophisticated system - as one might expect from knowledge of the original radar sensor for air bag inflation they produced. The set is uniquely different from others in several ways but, from the limited information now available, the results seem to be about on par with Nissan.

- Nissan Motor Co., Ltd., Yokosuka and Mitsubishi Electric Company – Monostatic, Pulsed Set with Superheterodyne Receiver, Pulsed Doppler (Figure 3-2)

Range	5 to 100 m ± 3
Relative speed	3 to + 128 km/h ± 1
Response time	45 ms
Transmitted frequency	24 GHz
Local oscillator	23.84 GHz
IF	160 MHz
Peak power	20 mW
Pulse width	20 ns
Rise time	5 ns
PRF	

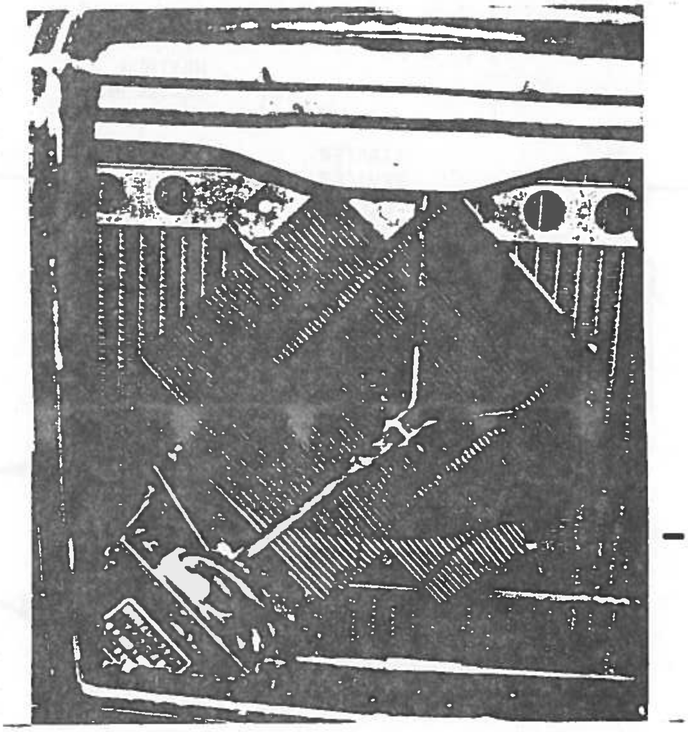


Figure 3-2. NISSAN RADAR SYSTEM ANTENNA

Antenna, parabolic, striated $3.5^{o} \times 3.9^{o}$ at 45^{o} linear polarization

Range Algorithm:

$$S_a = \frac{V_r(2V_a - V_r)}{2\alpha} + V_a t_d + K$$

Sophistication: Level II+

Nissan used the results of experiments of a target discrimination study employing road tests using a short pulse modulation microwave radar with a microprocessor-based electronic circuitry (Figure 3-3). A restricted radar detection range, in accordance with steering angle data, was found to be effective in reducing non-hazardous target detection. However, technological problems in the development of an automatic braking system still remain.

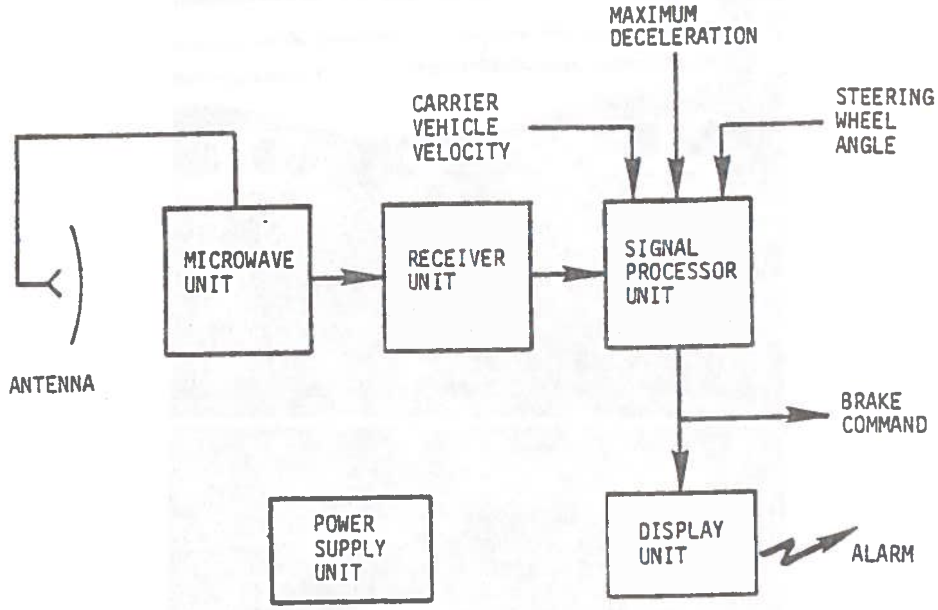


Figure 3-3 SCHEMATIC OF NISSAN RADAR SYSTEM

It is likely that Nissan approached the problem from several ways. It is known that they used the usual approach of taking TV tapes of the highway clutter and used them to optimize the circuitry. But likely they also played computer programming games to optimize performance. Because of their unique pulsed Doppler RF head, they use only one Gunn oscillator yet have the advantages of a superhetrodyne receiver. Since it is monostatic they require only one antenna. Although their present 24 GHz, striated parabolic antenna reflector is very expensive, they are aware that production units would move the antenna away from in front of the radiator and make it smaller. Therefore, ultimate production cost is a guessing game, but it appears they could probably reduce it to an MIC with mirrors – dramatically dropping costs to the neighborhood of a few 10s of dollars.

The unit does very well on highway clutter, for $\alpha > 0.5$, although there is room for improvement. They do much better than the German units do but presumably and primarily because they reduce range for automotive braking where α is large and T is put equal to zero.

- RCA Laboratories (Princeton, NJ) and The U.S. Department of Transportation (Washington, DC) – Bistatic, FM-CW Set, Including an Isolator

Range	7 - 30 m
Relative speed	0 to 60 m/s
Response time	
Transmitted frequency	17.5 GHz
Modulation frequency	977 Hz
Frequency deviation	50 MHz
Antennas, printed circuit	3^o horizontal
Power output	10 mW
Sophistication:	Level II+

With the system adjusted for practically no false alarms, a target of 1 m^2 is recognized at 23 m and braking is initiated if the closing rate is high enough. In a car traveling at 25 m/s against a fixed object, this action results in a reduction of crash energy by up to 45 percent. Further work could increase the minimum range to 30 m.

This work is the principal work openly available in the United States. It is excellent work, of high quality. They give a cost estimate of some $177.00 for quantity production, including certain sensors and hardware in addition to the electronics and the antenna system. It appears that the printed circuit antennas, the placement in front of the car, limit the ultimate price reduction. The isolator is inherently expensive. Were they to combine their techniques with the pulsed Doppler technique of Nissan, for example, then move up to 50-60 GHz as Toyota has done, the results would probably be impressive.

- Standard Elektrik Lorenz Ag (SEL) and Damiler Benz, Stuttgart, Germany – Bistatic FM-CW Set with Sawtooth Modulation, Homodyne (Figure 3-4)

FIGURE 3-4. SEL-BENZ RADAR SYSTEM

Range	0 to 130 m $\pm$ 2.5 m
Range resolution	10 m
Relative speed	0 to 160 km/h
Response time	100 ms
Transmitted frequency	35 GHz
Modulation frequency	29 kHz
Frequency deviation	2.4 MHz/us
Antennas	2.5^o horizontal 3.5^o vertical
Power output	20 mW

Range Algorithm:

$$S_a = \frac{V_2^{\,2}}{2b_2} - \frac{V_1^{\,2}}{2b_1} + TV_2$$

SEL approached the problem by feeding actual data into a programmed PDP-8 and then used various traffic situations to produce their best data processing procedures. They use time delays, maximum range limitations, and steering-wheel angle sensors.

A Gunn oscillator is used, two parabolic reflector-type antennas smooth at 35 GHz, and an RF connection between them. A $15 allowance is made for the electronics; however, the front end, residual, high-quantity production costs will remain high because of the high precision machining requirement.

The autonomous collision avoidance system developed in conjunction with Daimler-Benz AG (Figure 3-5) consists of a radar sensor using the FM/CW method, an opto-acoustic warning, and a microprocessor which reduces false alarms through logical and time analyses as well as calculating the current vehicle spacing.

Proper system operation is automatically checked by a special test cycle each time the equipment is turned on.

Trial runs have provided satisfactory results even under adverse environmental conditions. Several passenger and commercial vehicles will be equipped with the collision avoidance system in a larger test program. This will be concluded in 1980, providing evidence on effectiveness, reliability and driver acceptance.

The work is subsidized by the Federal Ministry for Research and Technology.

- VDO Adolf Schindling Ag, Frankfurt Main (In Conjunction with BMW, Munich) – Bistatic, Pulsed Set with Superhetrodyne Receiver (Figure 3-6)

Range	1 to 120 m ± 0.5
Relative speed	0 to + 200 km/h
Response time	250 ms
Transmitted frequency	35 GHz
Local oscillator	35.3 GHz
IF	300 MHz
Peak power output	300 mW

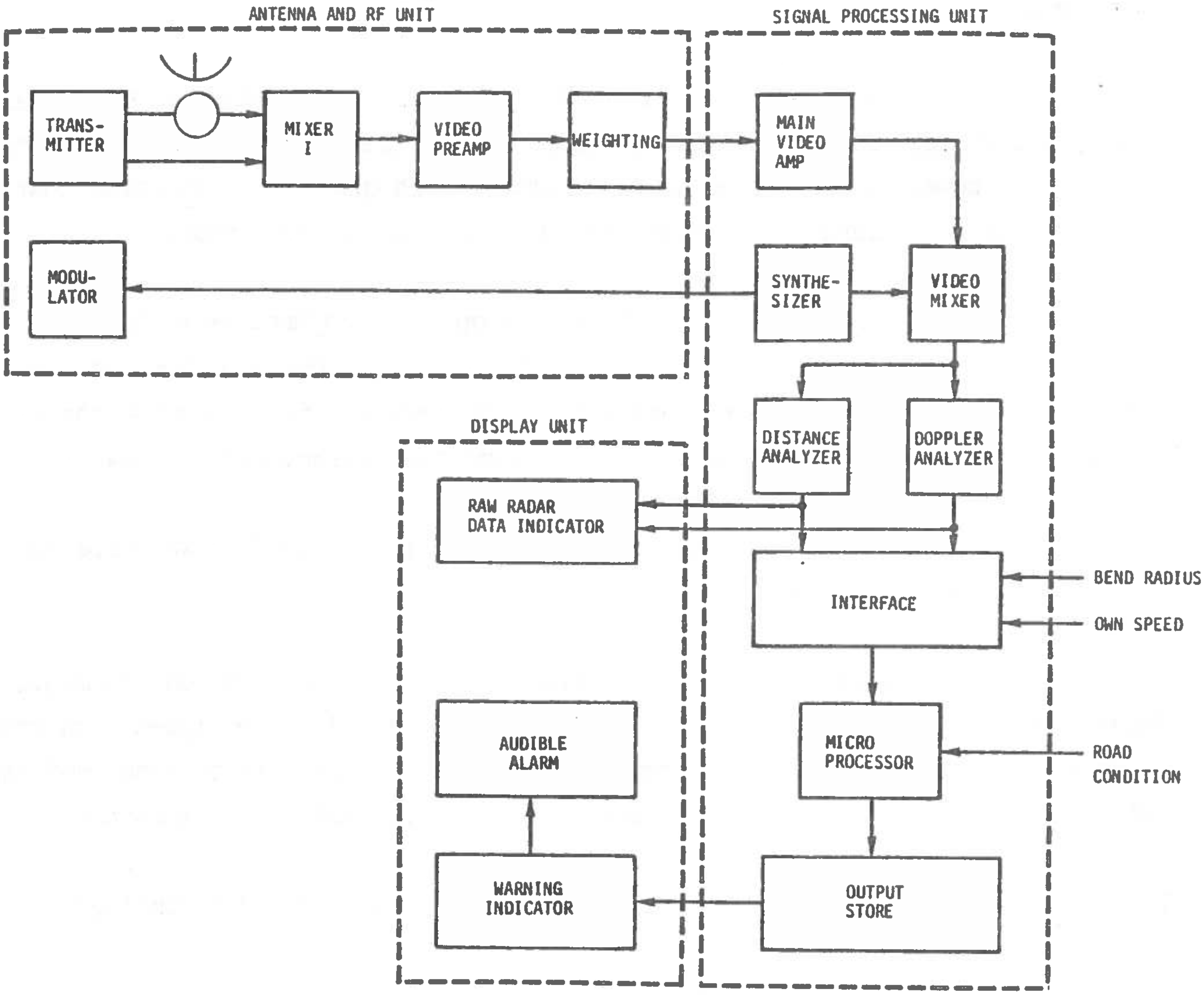


FIGURE 3-5. OVERALL BLOCK DIAGRAM OF THE RADAR ANTICOLLISION WARNING SYSTEM SHOWING THE DIVISION INTO 3 SUBUNITS

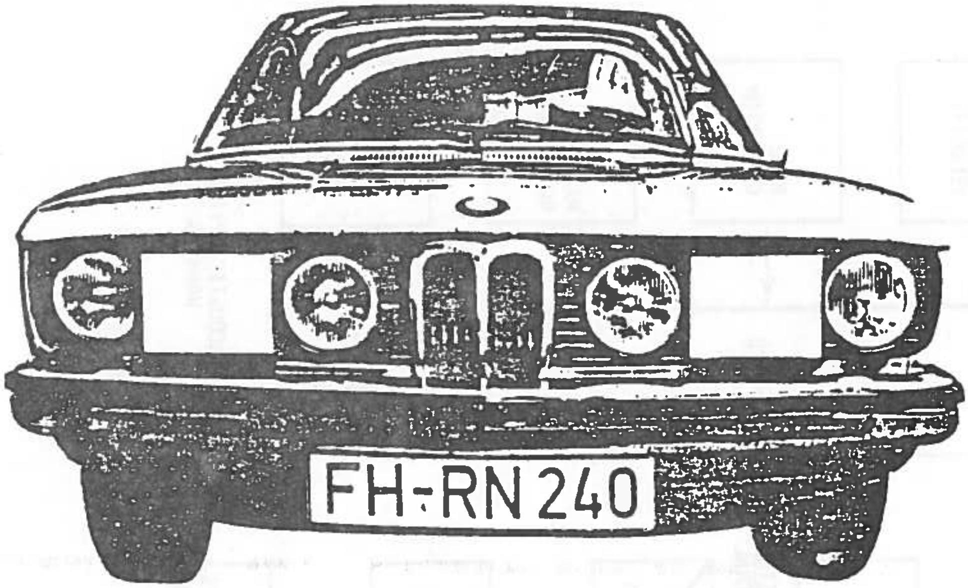


FIGURE 3-6. VDO - A. SCHINDLING RADAR SYSTEM

Pulse width	30 ns
Rise time	5 ns
PRF	250 kHz
Receiver BW	100 MHz
Antennas, 3 dB points	2.5° horizontal
	3.5° vertical

Range Algorithm:

$$S = \frac{V_2^{\,2}}{2b_2} - \frac{V_1^{\,2}}{2b_1} + TV_2$$

Sophistication: Level II

VDO approached the problem by using video tapes of traffic situations to program an 8-bit microprocessor, together with an analysis of the echo. They are working on beam scanning for curve recognition. (See Figure 3-7.)

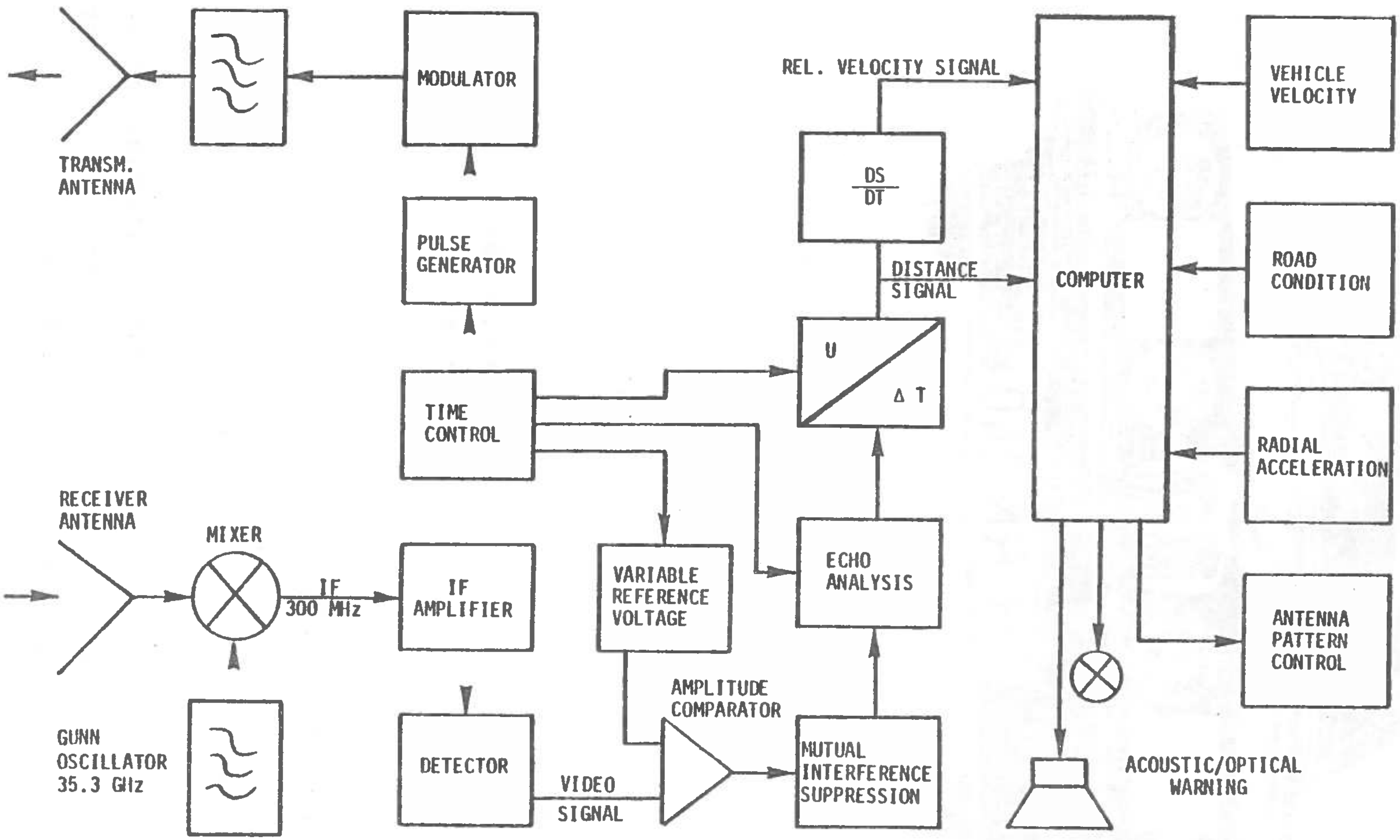


FIGURE 3-7. SCHEMATIC FOR VDO ADOLF SCHINDLING RADAR SYSTEM

Two Gunn oscillators are used, and two parabolic reflector-type antennas smooth at 35 GHz. A $25 allowance is made for the electronics. The front end, residual, high-quantity production costs will remain high because of precision machining requirements.

The unit does better on highway clutter than the Bendix units, but not as well as some others, although the techniques they are using seem promising in the long run.

3.3.2 System Characterization and Definition

3.3.2.1 False Alarm Rate

The radar cross-section of an object is determined by its size, its orientation and shape, and its electric properties. Unfortunately, for our purpose there is no direct correlation between electrical properties and physical properties. An electrical conductor will strongly reflect all frequencies considered here. If a conducting target is either the size of a wavelength or if it is curved to focus the reflected beam towards the radar, it will return strong signals. The return from a large flat surface is nearly proportional to the surface area oriented towards the antenna; it does not matter whether the surface is metal foil or the side of a bridge. In general, non-conducting objects yield a far smaller return than conducting ones. An important parameter is a far smaller return than conducting ones. An important parameter is the object's electrical permittivity. A 6-inch tree and a man, a sign post and a cement pillar, or two motorcycles and a car, can look almost alike to radars, while a chain-link fence may appear as a solid object.

There is no way a radar can tell a concrete-filled metal barrel from an empty one, or a loose one from one attached to the earth.

For these reasons some false alarms are inevitable. No radar design can totally eliminate them without, at the same time, becoming so cautious as to be useless.

3.3.2.2 Percentage of Real Targets which are not Detected

All of the sets considered have sufficient sensitivity to detect automobiles at a range of 100 m. Detection probability depends upon noise distribution and the signal level. We assume all vehicles are in the beam long enough so the probability of detection is unity. This will be seriously in error only if the logical programming to detect actual-from-false targets introduces a measureably large probability of determining real targets to be false ones. That, in turn, depends upon the logic and the logic system in each case and we have no definitive information on them.

Targets with a lower probability of detection are those whose radar cross section is low enough for its return signal not to be many times larger than the noise level. Two-wheeled vehicles, dry trees, and animals have cross sections likely to place them in this category. Our experience with the Bendix system is that the probability of detection of a dry tree or a human being is very small, while two-wheeled vehicles are generally detected at no more than 10-20 meters. Four-wheeled vehicles are reliably detected at ranges in excess of 50 m.

3.3.2.3 Acceptable False Alarms and Missed Target Rates

An acceptable level of false alarms and missed targets as a minimum requirement for automotive radar system is somewhat difficult to define. Ideally, the system should have zero false alarm and zero missed target rate.

If we look at two different levels of radar braking systems, namely warning-only and automatic braking, the requirement of false alarm and missed target rate to approach zero becomes very important in the automatic braking system. In the case of the warning only system, a frequency of false alarms that a driver can tolerate can depend significantly on the individual. It is generaly believed that false alarm count in a range of 1 to 3 for a typical driving of 100 kilometers may be acceptable to an average driver, if the system is warning only type.

The IITRI Report (Reference 9) classified false alarms and missed targets as shown below:

- False Alarms

The conditions whilch relate to false alarm, i.e., undesired braking due to non-hazardous objects or situations, may be classified as:

Type 1: Non-hazardous vehicle trajectories which cross the radar field-of-view (FOV), e.g., opposing traffic flow on curves, vehicle crossings in straight line paths, etc.;

Type 2: Objects in the radar FOV on the same path, e.g., railroad tracks, water splashes, rain, and snow;

Type 3: Objects in the radar FOV, but not on the same path, for example, guardrails on curves, overpass structures, road signs, trees, etc.;

Type 4: Other radar echos (crosstalk);

Type 5: Other radar transmitters, for example, from opposing traffic flow;

Type 6: Other electromagnetic signals, for example, police radar, radio, etc.; or

Type 7: Malicious interference.

Solutions to these problems lie in several directions and include the possible approaches indicated in Table 3-3. Note that the solution to Type 1 false alarms - non-hazardous vehicle trajectories - requires the measurement of target lateral velocity, and calls for a radar which can provide target angular rate of charge information regardless of whether an independent or cooperative approach is used. Similarly, the Type 4 and Type 6 false alarms can both be handled by means of a distinctive code (each automobile) to allow discrimination against false alarms from echo, cross-talk and head-on radar encounters.

TABLE 3-3. POTENTIAL FALSE ALARM SOLUTIONS

False Alarm Type		False Alarm Solution
Type 1 -	Non-hazardous trajectories	Angle-sensing radar to provide lateral velocity; trajectory analysis performed by processor.
Type 2 -	Non-hazardous objects in FOV, in same path	Echo analysis, time history, doppler
Type 3 -	Non-hazardous stationary objects in FOV, not in path	Time history
Type 4 -	Other radar echoes (cross-talk)	Own coding
Type 5 -	Other radar transmitter (head-on radar)	Reverse polarization, own coding
Type 6 -	Other e/m signals	Own coding
Type 7 -	Malicious interference	Echo analysis, time history, doppler

- Missed Targets

The situations which relate to missed targets due to blinding, masking, multipath, etc., include the following:

Type A: Blinding due to radars in opposing traffic flow.

Type B: Blinding due to rain, snow, etc.

Type C: Blinding due to radome icing, dirt, mud, etc.

Type D: Masking due to ground clutter, for example, road backscatter occuring in the radar FOV due to a road dip profile, or masking clutter from non-hazardous objects such as road signs, trees, etc.

Type E: Large vehicle masking produced by a large vehicle at a longer range overriding the echo from a smaller vehicle at a relatively closer range, e.g., semi-trailer vs. compact car or motorcycle, etc.

Type F: Multipath fading or loss of target when the range is such that the target is in one of the range nulls.

Solutions to these problems include the approaches indicated in Table 3-4.

TABLE 3-4. POTENTIAL MISSED TARGET SOLUTIONS

Missed Target Condition		False Alarm Solution
Type A -	Head-on blinding	Reverse polarization; frequency selection
Type B -	Rain backscatter	Pulse radar approach for frequencies above 20 GHz
Type C -	Radome fouling	Self-test alarm sensitive to radome backscatter level; automatic housekeeping mechanism
Type D -	Clutter masking and clutter discrimination	Doppler shift
Type E -	Vehicle masking	High range resolution radar (pulse compression)
Type F -	Multipath fading	Beam control or frequency diversity

3.3.2.4 Adequacy of Equipment Functioning in Heavy Rains

The basic ideas are described in the Grimes & Jones article, the pertinent portion of which follows.

The conclusion is that reduction in range due to scattering from the beam is not particularly significant at the ranges of automotive radar. Although sensitivity is reduced in heavy rainfall, so are driving speeds and the necessity for an extended range.

Beam back-scatter using pulsed techniques is not a severe problem in pulsed sets since the rain return may be limited to that within a particular range gate. Neither is rain a problem at X band. Rain is, however, a problem in CW sets at the higher frequencies. Problems peak at the frequency for which the ratio of drop radius to wavelength is 2π. Rain drops of 4 mm diameter, for example, produce maximum interference at about 19 GHz, then drop to a low value again at about 32 GHz. Table 3-5 shows drop diameter versus frequency of first maximum and first minimum in the scattering.

TABLE 3-5. DROP DIAMETER VERSUS FREQUENCY OF FIRST MAXIMUM AND FIRST MINIMUM IN THE SCATTERING

Diameter of Raindrops (mm)	Frequency (GHz)	
	First (maximum)	First (minimum)
1	95	162
2	48	81
3	32	54
4	24	41
5	19	32

Proper choice of band filters in CW sets to gate away frequencies close-in to the carrier may be used to reduce interference. Nonetheless rain interference in CW sets remains as a nontrivial problem.

As a final note, by transmitting and receiving in different polarizations, an additional 12-15 dB rain-noise reduction is achieved. This may be accomplished using either crossed linear polarizations or circular polarization.

Figure 3-8 shows the one-way propagation loss per kilometer as a function of frequency for two different atmospheric conditions. The atmospheres chosen represent extremes of normal operating conditions within the continental United States. Therefore, all normally encountered operational conditions within the U.S. lie between the two curves. Several observations can be made; namely: 1) relatively broad absorption lines exist as a result of spectrally selective absorption by certain atmospheric gases or vapors; 2) doubling the frequency approximately quadruples the loss of the base curve; 3) the absorption increases with the number of gaseous molecules in the beam, i.e., the high atmospheric pressure the greater the absorption. Important absorption lines for radar purposes are the water-vapor absorption lines at about 22.2 GHz and the oxygen absorption line at about 60 GHz.

More specifically, power returned to the receiving antenna per kilometer range is reduced by $10^{-0.24}$ as a result of atmospheric absorption, where A is the attenuation shown in Figure 3-8. The maximum anticipated automotive radar range required for station-keeping applications is not expected to exceed 100 m. Attenuation at sea level, at 60 GHz and 100 m (each way) range, is about 3.2 dB, a figure not too excessive for automotive purposes. Therefore, in the main, the two absorption maxima are important, not because of the magnitude of the absorption, but rather because the presence of higher absorption has curtailed use of these frequencies for spectrally competitive nonautomotive applications.

Rain or splashed water scatters energy from the radar beam. Scattering does two things; namely, it subtracts desired power from the beam, and it reflects undesired power back towards the radiator-receiver, thereby obscuring the target. Figure 3-9 exhibits the one-way beam attenuation per kilometer of range under various rain and fog conditions as a function of frequency. As was the case for atmospheric attenuation, at no applicable frequency is the rain attenuation large enough to seriously compromise operation of proposed automotive radars.

On the other hand, back-scatter from water is large enough to interfere seriously with CW radar operation. Each raindrop acts as an echoing target wherein the return is maximum when the raindrop circumference is about one wavelength, then it oscillates but remains effectively large for all shorter wavelengths, as shown in Figure 3-10. Because very large numbers of raindrops exist per cubic meter

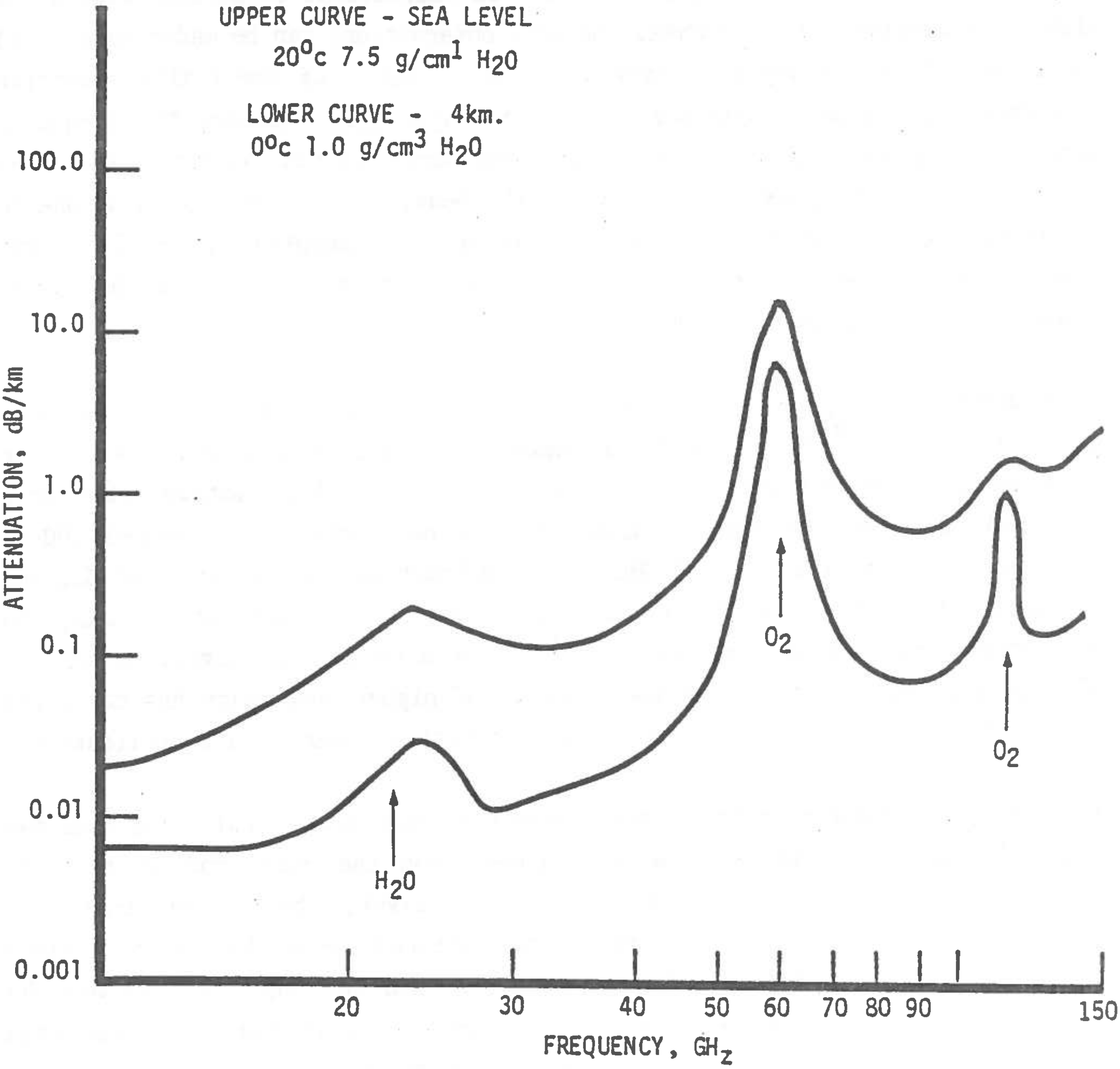


FIGURE 3-8. ATMOSPHERIC GASES, ATTENUATION SPECTRUM.

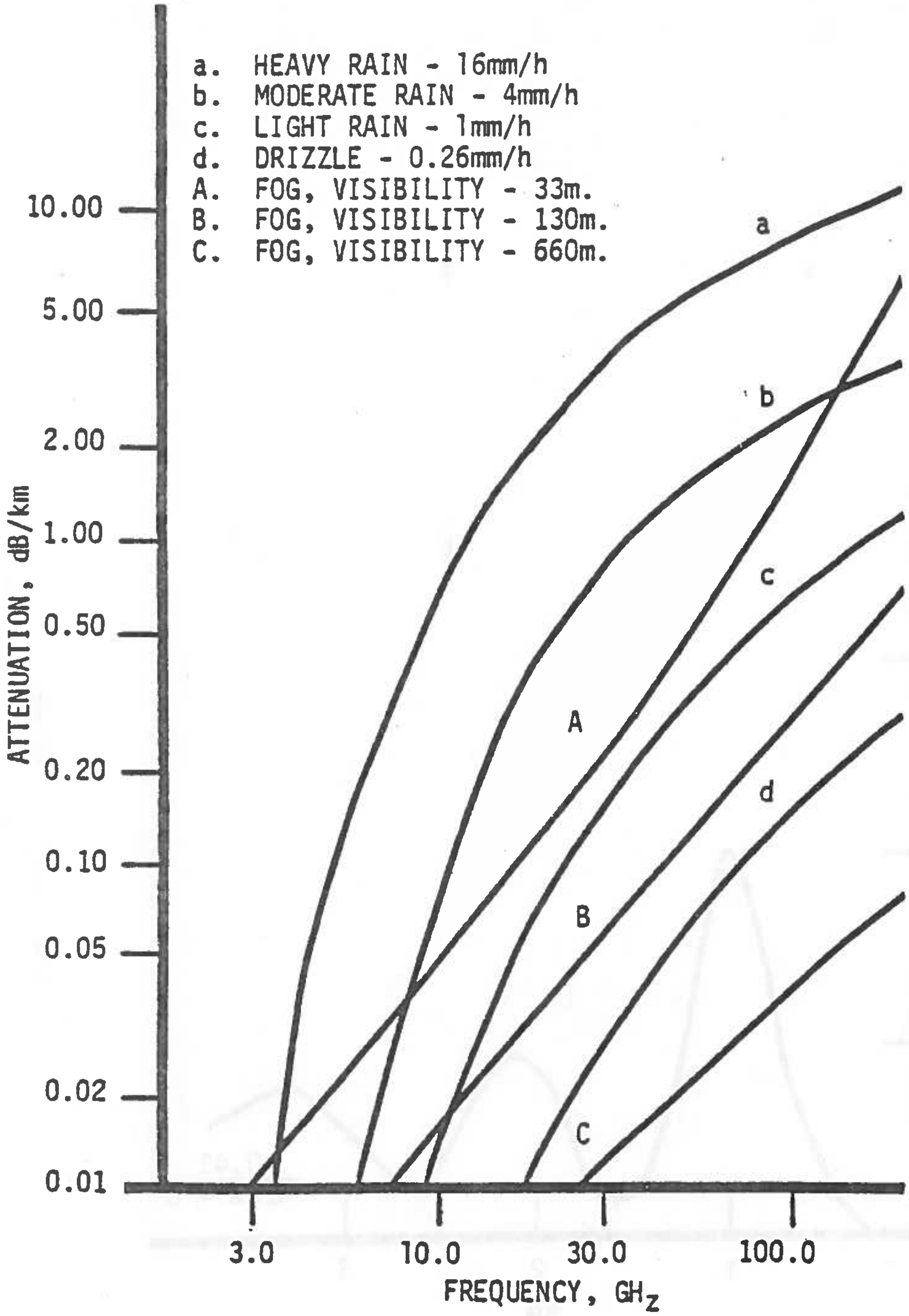


FIGURE 3-9. RAIN AND FOG, ATTENUATION SPECTRUM.

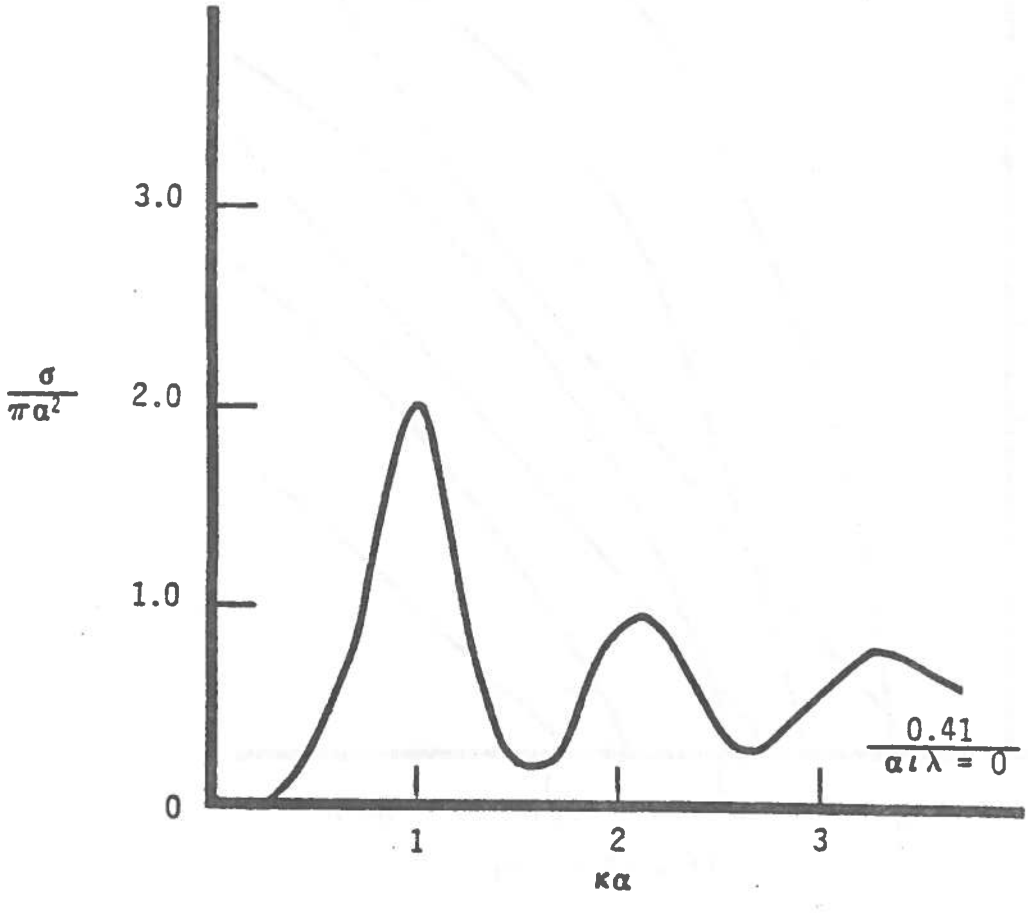


FIGURE 3-10. RADAR CROSS SECTION FOR RAINDROPS OF RADIUS AT FREQUENCY OF WAVELENGTH $\lambda = 2\pi/\kappa$.

periods of rain, and because drops are typically present over the entire path of the radar beam, raindrops can decrease the received signal-to-noise ratio to mask traffic targets otherwise easily detectable. For uniform rainfall and a target at range R of cross-section σ the ratio of power from the open (nongated) receiver due to rain P_r to that due to the P is:

$$P_r/P = (2\eta R^3)/\sigma \quad ,$$

where η, the rain cross-section parameter, is the sum of cross sections over all drops per unit volume

$$\eta = \sum_i \sigma_i \quad ,$$

where η has the dimensions of inverse length. Values of η computed as a function of frequency for several rain conditions are shown in Figure 3-11.

Figure 3-11 shows that a target of 1-m^2 cross section will produce at least a unity power signal to rain-generated noise ratio at a distance of 3 m for all frequencies of interest and for all rain models considered. On the other hand, at a distance of 33 m, results depend upon the rain condition. The unity signal-to-noise ratio condition is not met during a rainfall of 4 mm/h at any listed frequency; it is met at K-band and below during a rainfall of 1 mm/h, and it is met at E-band and below during a rainfall of 0.26 mm/h or less. The condition deteriorates as R^3 for larger ranges.

Rain-dependent S/N ratios from complex targets can be improved by use of polarization discrimination. Either monostatic, circular polarization, or bistatic cross-polarized antennas can be used. Circularly polarized rain clutter reduction depends upon drop ellipticity; nevertheless, experience indicates that rain clutter can be reduced by as much as 20 dB over direct return. Returns from complex objects such as automobiles are decreased approximately 3 to 5 dB. Such reductions suggest SW usage for a unity cross-section target of 100 m and unity signal-to-noise ratio over frequencies up to E-band for the rainfall considered.

Figure 3-11 is applicable only when the receiver is left open. The receiver can be gated to accept only the return from targets lying within time interval ΔT,

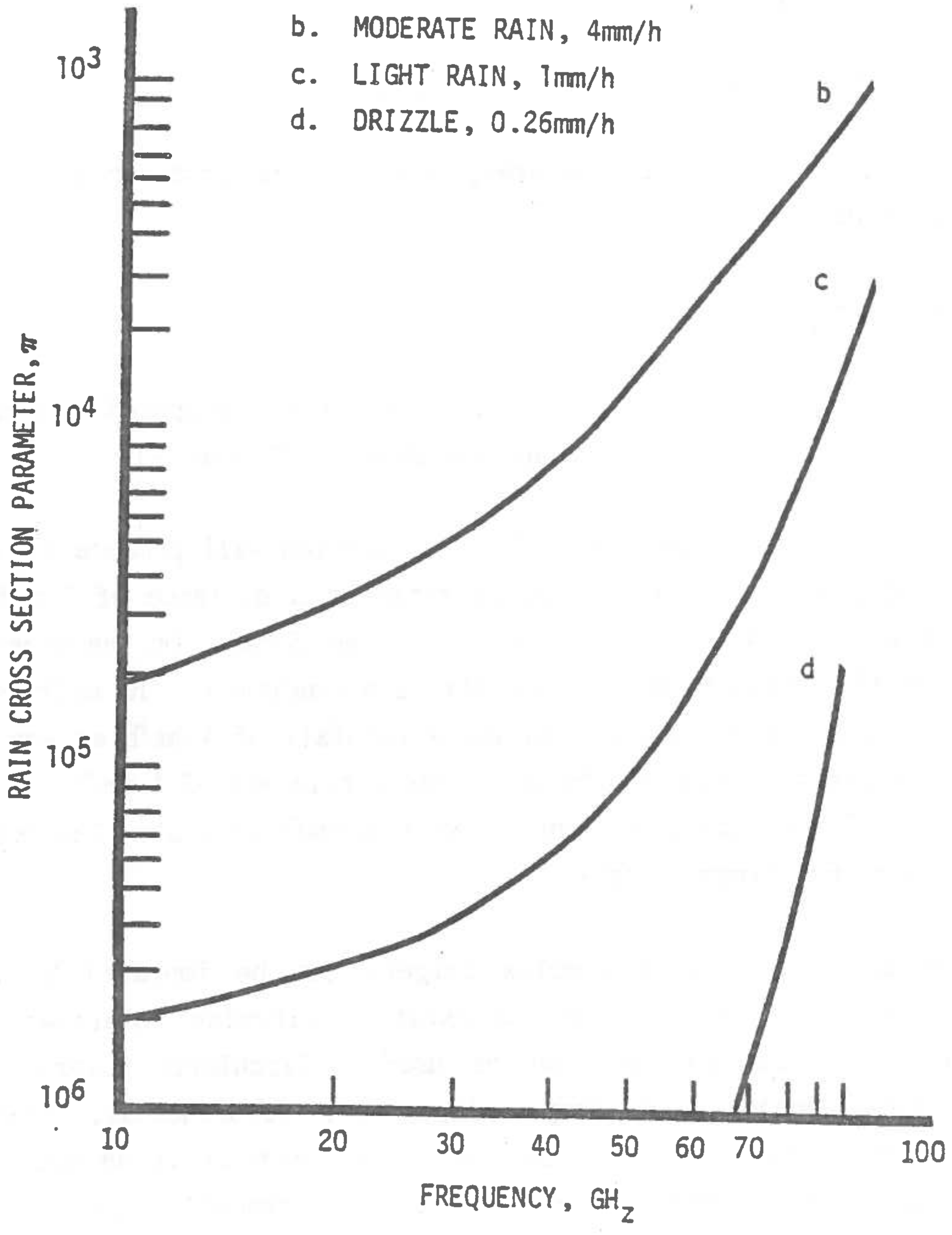


FIGURE 3-11. BACKSCATTER SPECTRUM FROM RAIN.

thereby reducing rain clutter. The time-averaged gated rain return P_r for pulsed radar can be obtained as:

$$P_r/P_T = \frac{\pi D^2 L \eta}{128\ R^2}$$

where L is the length of the pulse cT, T is the pulse duration, D is the diameter of the antenna, and R is the range; and where ideal antennas and circuits are assumed. P_r is peak transmitter power. A typical value of D in automotive applications is 0.2 m, while an expected value of L would not exceed 3 m. For these values, expected ranges and frequencies will have signal-to-rain-generated-noise ratios in excess of unity.

3.3.2.5 "Blinding" of Radar by Other Transmitters

Special care must be taken to preclude spectral interference produced by or acting upon automotive radar. Emitted radiation from automotive radars might not only affect existing communications and other devices, depending upon the frequency allocation and frequency tolerance, but also each other. The importance of the effect upon automotive radars depends upon the design objective of the radar and the particular roadway environment in which it occurs. The consequences of interference with a radar speedometer during normal driving operations might not be serious, while interference during emergency braking might be. The consequences of interference with an air-cushion deployment radar could be most serious. A particularly significant and highly probable example of interference is blinding produced by two vehicles on a two-lane highway, especially on curves. Antenna directivity coupled with polarization isolation will alleviate but not completely solve the problem.

Typical round-trip signal attenuation is in the range of 80-90 dB. Polarization isolation is not expected to average more than 30 dB.

3.3.2.6 Performance of Radar on Curves

Radar performance on curved roads shows a need for compromise between missed targets and false-alarms. The driving experience with radar equipped vehicles has shown that the false alarms primarily occur on curved roads.

Figure 3-12 illustrates a radar equipped vehicle on a curve. The radar beam reaches the outside edge of the curve at a distance of S ahead of the vehicle. Limiting the range of radar detection on curves to a distance shorter than distance S could be effective in preventing the false-alarm. S in Figure 3-12 is given by the relation:

$$S = \left(\frac{\ell}{\beta}\right)^2 \left(\beta + \frac{\theta B}{2}\right)^2 + 2\,\frac{\ell \Delta r}{\beta} + \Delta r^2 - \frac{\ell}{\beta}\left(\beta + \frac{\theta B}{2}\right) \text{blanks} \quad ,$$

where s = Limited radar range

ℓ = Wheelbase

β = Front wheel angle

Δr = One-half of lane width

θB = Radar beamwidth.

A Nissan paper (Reference 10) reports that when the radar range was limited to 50 meters, they succeeded in completely elimininating false-alarms on curves with radii of curvatures larger than 1000 meters. For radii of curvatures smaller than 1000 meters, they report that the frequency of false-alarms was reduced to 3 in 100 kilometers of driving when deceleration constant *** in their range algorithm ($R = V^2/2$) was set to 0.4 and the rate became 1 in 100 kilometers when α was set to 0.6. R is the range in the above algorithm and V is the vehicle velocity.

On the other hand, the IITRI Study (Reference 9) showed that the road curvature limits the maximum range to values considerably smaller than the stopping distance required to avoid collision with a stopped vehicle. For example, on a curve with a radius of curvature of 1361 feet, the maximum range with a beamwidth of 2.5 degrees is 60 feet and the stopping distance required for a vehicle travelling at 55 mph will be about 128 feet under panic brake condition. The solution to this problem can be to scan the radar beam to increase the field of

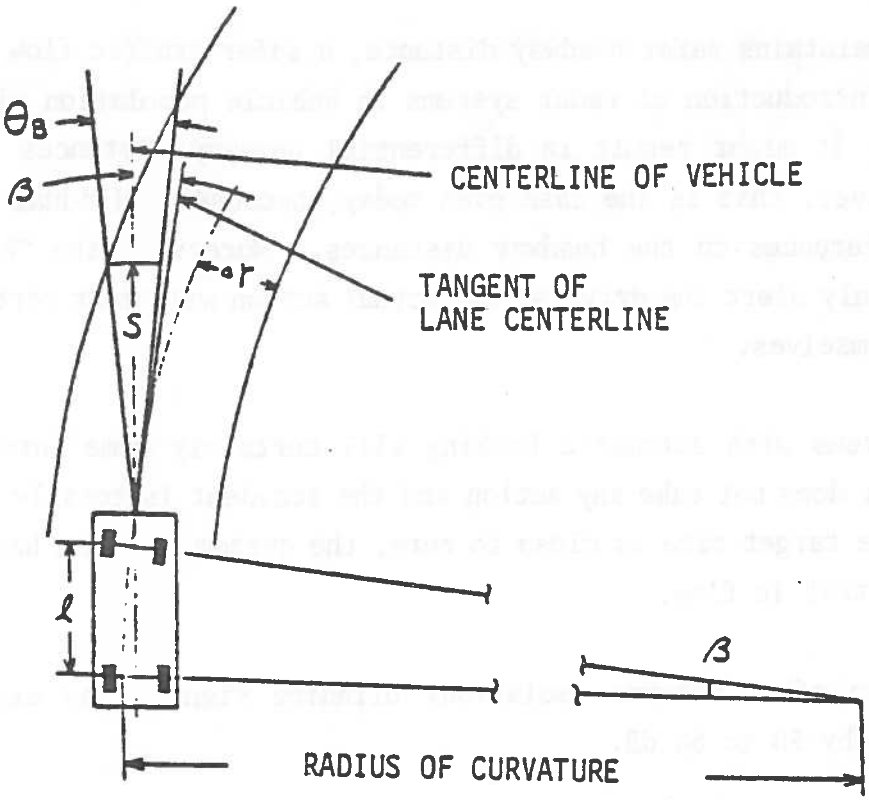


FIGURE 3-12. RADAR RANGE ON CURVE

view. However, such an increase in the field of view can lead to increased false-alarms.

The two illustrations above indicate the conflicting requirements and need for compromise on the radar performance design on curved roads.

3.3.2.7 Impact of Systems on Traffic Flow

Both Japanese and German radar system developers have done substantial amounts of in-traffic evaluation of warning-only experience, recorded and stored, as an input for their control logic optimization.

"Warning Only" radar can act as a good "driver-aid" and will warn the driver if the headway which is being maintained is not safe. If the driver needs the radar warning, and maintains safer headway distance, a safer traffic flow will result. As a gradual introduction of radar systems in vehicle population will occur, in the beginning, it might result in differential headway distances in chains of traffic. However, that is the case even today, because individual drivers have their own preferences on the headway distances. Moreover, the "Warning Only" systems will only alert the drivers; the actual action will most certainly depend on drivers themselves.

The radar systems with automatic braking will certainly come into effect only when the driver does not take any action and the accident is totally unavoidable. Hence, if false target rate is close to zero, the system will not have any advers impact on the traffic flow.

Therefore, even after antenna isolation, blinding signals may exceed that in return signals by 50 to 60 dB.

This problem may be quite satisfactorily solved, however, by properly coding the radar systems. For example, suppose the probability of blinding can be no more than 10^{-7}, and the probability of 10 similarly equipped vehicles having their beams directed towards a single receiver at one instance also to be 10^{-7}. Only 11 adaptively code radar channels need then be constructed, each with appropriate bandwidth, selectivity, and stability, to make the blinding probability sufficiently low. A particularly convenient means of coding, at least in the millimeter-wave frequency range where adequate spectral bandwidth is available, is coding by frequency selection. Frequency coding is not difficult to achieve; it is noteworthy that similar devices are presently used on multichannel Citizens Band receivers to search for signals.

As a further example, the pulsed power of pulsed systems may be randomly radiated with the aid of an intrinsic random number generator.

3.3.2.8 Biological Effects

The most definitive work pulished to date on the biological effects of nonionizing radiation is summarized in Janaury 1980 Proceedings. The salient features are:

1) The radiation is nonionizing.
2) The average output power per set is from 10 mW to 20 mW, somewhere in ther frequency range of Ku through W frequency bands, during which the skin depth, in most biological materials, ranges from a millimeter or less to about one centimeter.

Since the radiation is nonionizing, the effects expected are of two kinds, (1) thermal only, and (2) conductive affecting nerve cells.

Full sunlight on a normal area has an input power of about 100 mW/cm^2. Since most of the antennas have frontal surfaces of 50 to 700 cm^2, it follows that the output power density is 0.2 to 0.01 mW/cm^2 – a factor of 200 to 10,000 times less power density than direct sunlight and, of course, it is restricted to that portion of the body in contact with the antenna.

Another view of the power is by comparison with a typical handheld flashlight. They typically consume some 1200 mW of power, and radiate about 400 mW through a lens about 4 cm in diameter. Therefore, typical output automotive radar power densities are about 200 times smaller than the flashlight.

The worst possible scenario is with one in direct contact with the antenna, and the power density is the worst case of 0.2 mW/cm^2, which translates to an electric field intensity of about 400 V/m, or 0.4 V/cm. Firing of nerve synapses takes about 1 ms with a dc potential of some 0.02 V. Were the 0.4 V/cm to be transmitted into the biological system, a maximum of 0.02 V would occur each 0.05 cm. However, the field is ac with maximum period of 10^{-10}s; therefore, the threshold voltage for producing nerve synapsis has a pulse duration a factor of 10^7 too short. Neither is there any direct evidence that such action occurs.

For these reasons, and in the absence of any substantiating evidence to the contrary, we believe biological effects are minimum to nonexistent.

3.3.2.9 Vehicle Loading Effects on Beam Direction

A quick analysis of 1980 model U.S. vehicle suspension parameters indicated that the attitude angle change because of the vehicle's suspension deflection can be of the order of 2 to 3 degrees. The calculations were made on the basis of suspension data like suspension travel, spring rates and the vehicle's wheelbase. Extreme front heavy and rear heavy weight distributions were assumed within axle capacities to arrive at the above number. The pitching motion of the vehicle will not affect the lateral beamwidth of the radar. Some effects can be seen on the curves as a result of the vehicle's rolling motion and differential side to side load transfer and suspension deflection. However, the effect is not expected to be substantial.

3.3.2.10 Multiple Targets Problem

An example of a multiple target problem is when the radar equipped vehicle has a heavy truck and a passenger car ahead of it and both are within the radar range. In this case, the question arises whether the radar will be capable of distinguishing between these two and correctly apply the input received to make the decision. A similar situation can be envisioned where a heavy truck is ahead of the radar equipped car and in its range of detection; then a passenger car can cut in between the two vehicles. Can the radar detect that car against the background of the larger cross-section of the heavy vehicle? In both cases, the key appears to be for the radar to differentiate between the two targets based on their closing speeds and distances with respect to the radar-equipped vehicle.

This problem is tackled by radar control logic that incorporates gating and places the received in a series of gates within its range.

3.3.2.11 Multiple Path Effects

The most common multipath is that which includes a single ground bounce. Problems arise when the difference in path length is a half wavelength: phase cancellation occurs and the oberved echo can be so small as to drop totally from the radar system. The depth of the cancellation depends upon the reflectance of the roadway surface. At grazing angles for the frequencies of interest here, the reflectance typically approaches (-1). Since the depth of the minima is proportional to the difference between unity and the magnitude of the reflectance, the nulls may be very deep.

Generally speaking, for a radar carried a distance h' above the ground and a scatterer located a distance h'' above the ground, the distance L to the first phase cancellation is given by:

$$L = 4h'h''/\lambda \quad ,$$

where λ is the wavelength of the carrier beam. To estimate the distance at which this process begins, we put h' = h'' = 0.3 m and note that for frequencies of 10, 35, and 60 GHz the distance to the first phase cancellation is, respectively, 12, 42, and 72 meters. These numbers show phase cancellation to be a major problem at 10 GHz, a moderate nuisance at large ranges at 35 GHz, and an insignificant factor at 60 GHz.

A second problem area was thought to be multiple scattering centers on the same scattering object. For example, were the aspect angle of a leading vehicle to change, the magnitude of return from different portions of the vehicle. These scattering positions scatter with a given phase and they, too, may add in phase or out - one shifting to the other as the angle changes. Even a large object, by this means, might entirely dissappear from the radar's view.

Experience has shown that this latter effect is not too severe, probably because of the smooth and simple design of such commonplace highway objects as automobiles and road signs. Were automotive designs to change to protrusions, such as were commonplace in the 50's and 60's, such cancellation would be more common, but present auto designs minimize the effect.

3.3.2.12 Frequency Allocation Problem and Other EMS/EMC Problems

The selection of operating frequency for the automotive radar systems depends on several factors including:

- FCC frequency allocation;
- Rain backscatter blinding effect;
- Beam shape and antenna size tradeoff; and
- Availability of RF sources and microwave components.

The lower bound of the operating frequency range is dictated by antenna beamwidth and the maximum area available for the antenna aperture. The upper bound will depend upon the hardware cost and the selected performance parameters.

With a parabolic antenna and the selected beamwidth in the range of 1 to 5 degrees, the operating frequency range is: 17 GHz < Operating frequency <87 GHz with about a 10 inch antenna aperture.

The selected operating frequency also will be governed by applicable FCC regulations. The influence of rain backscatter, multipath effects, etc. are discussed elsewhere in the report.

One area of concern is the safe radiation level for the human beings. At present the maximum safe level specified by the American National Standards Insitute (ANSI) is 10 mW/cm^2 for continuous exposure. The IITRI report (Reference 9) stated that the use of 100 mW final output stage, feeding a uniformly illuminated 20 cm x 20 cm aperture resulted in a radiation power density 0.25 mW/cm^2, which is well below the ANSI standard.

3.3.2.13 Various Delay Times Between First Detection of a Target and Final Application of Brakes

The delay time between the first detection of a target and final application of brakes will include the following factors:

1. Radar system delay;
2. Radar system logic decision time;
3. Driver reaction time; and
4. Brake system delay time.

- Radar System Delay

Cycle times of different systems are in the order of 20 to 100 milliseconds. This is a relatively very short span compared with the other delays in the system.

- Radar System Logic Decision Time

The received signal is continuously processed through the set logic. After the first detection, no action is taken until the hazardous situation is identified. The radar system logic decision time will depend on the logic itself, the vehicle condition like steering input, brake input that are monitored and on the level of signal processing used (e.g., Level III may incorporate "gating" and will result in longer delay times). In general, the logic decision time can be in the order of 0.1 to 0.5 seconds.

- Driver Reaction Time

Driver reation time is a variable factor depending on the driver or an individual and the circumstances. In general, the driver delay can be in the range of 0.5 to 3 seconds. Bendix used 0.9 second for an average driver confronted with a surprise situation; 0.5 second can be used for an alert driver and an intoxicated driver can take up to 3 seconds for any action.

- Brake System Delay Time

For automatic rapid brake actuation, it will take about 0.1 second for the brake line pressure to reach the maximum.

3.3.2.14 Reliability and Maintenance Problems

A radar system has not yet been developed to a stage where it has been offered as an option or tested in fleets. However, experience from prototypes and from non-automotive fields suggests that they should be fairly reliable and maintenance-free systems.

3.4 SYSTEM COMBINATIONS FOR EVALUATION

A general review of the collected system description and performance data indicated that the key variables that influence the system performances were the signal processing and the control logic. The three levels of the signal processing can be defined as follows:

<u>Level I</u> There is no difference between acquisition and detection of a target, because the radar time delay is zero. This gives rise to many false alarms since any peak of noise exceeding the threshold is considered to be a valid signal, and starts the braking process.

<u>Level II</u> A time integration is performed during a certain period of time "Tdel"; it increases the signal-to-noise ratio, and recognizes a possible peak of noise exceeding the threshold during a short period of time. Two different approaches are possible: either a constant range delay, or a constant time delay. The latter is more efficient at low speeds than at high speeds, since the distance covered before detection increases with automobile velocity

<u>Level III</u> A time integration is included with an elaborate braking algorithm allowing predetermination of target trajectory. In this way, targets with collisionless trajectories are eliminated. This system requires very elaborate

signal processing, performed by a microcomputer to calculate the trajectory of a target, and to recognize the signature of some non-hazardous targets such as guardrails, road signs, and bridges.

These three levels correspond to an increasing efficiency in reducing the false alarm rate. Experimental data have led to the following estimate:

For every 100 km under normal driving conditions, Level I would result in an average of nine false alarms, Level II in four false alarms, and Level III in one or possibly no false alarms.

Actual system combinations that were selected for the benefit evaluation are described later in Section 4. The description includes control logic and the key parameters.

3.5 SYSTEM COST/PERFORMANCE RELATIONSHIP AND LIFE CYCLE COSTS

None of the reviewed radar braking systems is at a stage where production costs in a selected volume of production can be accurately estimated.

The cost estimates quoted, at times, are with no reference to production quantity, year of production or the level of the cost structure (manufacturer's, OEM, dealer or consumer level). This makes accurate prediction very difficult.

3.5.1 Production Cost Estimates

One cost estimate available was from the Bendix Study (Reference 1). The study report published in 1974 quoted the cost estimates shown in Table 3-6. The rationale for the Bendix cost estimate is given below and is taken directly from the above-referenced report.

"The cost of the automotive radar to the consumer is the most difficult subsystem cost to estimate with confidence. The radar cost uncertainty is reflected in the

TABLE 3-6. ESTIMATED COSTS TO THE CONSUMER OF AUTOMOBILE RADAR BRAKE SYSTEMS

(a) Estimated Consumer Cost of Non-cooperative Radar Brake Systems

(The automatic system includes a brake and throttle modulator not found in the semi-automatic system.)

System	Auto Stop	Bendix	Radar Control System	VDO
Semi-automatic	--	$105-$200	$875	Less than $875
Automatic	$350	$150-$272	--	--

(b) Consumer Costs of 2-Wheel Anti-Skid Systems

Automobile Company	Consumer Cost
Ford	$197
General Motors	$206
International Harvester	$207

price quotations for one of the major components, the Gunn oscillator, by two well-known manufacturers.

"Microwave Associates offers a Coppler transceiver consisting of a Gunn oscillator, ferrite circulator, and mixer assembled in a compact waveguide package for $5.00 to $7.00 in quantities of one million. These units are X-band (10.525 GHz). Output power ranges from 10 mW to 100 mW. These low cost transceivers cannot be used without modification by any of the six radars considered in the study. Microwave Associates offers varactor tuned Gunn oscillators for AFC, FSK, FM-CW as an available option, presumably, at increased cost.

"Varian quoted prices on Gunn oscillators VAS-9015, VSK-9014 and VSU-9012 in frequency bands 12.4-18 GHz, 18-26.5 GHz and 26.5-40 Ghz, at 25 mW or 50 mW power output and with different mechanical and electrical tuning ranges. Models S1 and S2 in each of the three frequency bands are presently priced at $495 and $595; $745 and $1,595; and $1,250 and $3,650 in small quantities. For example, Gunn oscillators VSK-9014S1 and VSK-9014S2 both operate in the 18-26.5 Ghz band, both are rated at 25 mW. S1 has an electrical tuning range of 30 MHz and is priced at $745 while S2 has an electrical tuning range of 100 MHz and is priced at $1,598. Varian estimates that prices might drop by one-half in production quantities of 100,000.

"From this brief survey it is evident that the cost of the Gunn oscillator is a large variable. It and other components in the transceiver module might cost as little as $5.00 or as much as $1,825 depending on operating frequency, on output power, and on electrical and mechanical tuning requirements.

"Price estimates were obtained for four of the automobile radars. Three of these were O.E.M. price estimates obtained in telephone conversations with no qualification of the dollar figure by year, production quantity, performance or other significant influence on cost. Mr. Davis estimated that the Radar Control Systems radar O.E.M. price might be $25.00. Mr. Flannery estimated the O.E.M. price of the AutoStop radar system as $100.00; and Mr. Bielefeld estimated that the VDO system would be priced at less than $250.00. The corresponding estimated consumer prices are approximately $875.00 or less for the radars of Radar Control

Systems and VDO, both of which are semiautomatic, and about $350.00 for the AutoStop system, an automatic system.

"Engineers at some of the manufacturing divisions of Bendix Corporation which are suppliers to automobile manufacturers have, from time to time, been asked to estimate the cost to the consumer of the radar and other subsystems. The costs to the consumer of the Bendix radar configured either as an automatic or semi-automatic system appear in Table 3-6 shown earlier. These consumer costs are tabulated along with those estimated for AutoStop, Radar Control System, and VDO. It is again observed the VDO radar employs a superheterodyne receiver and that the detection range is the longest of any system surveyed; the accuracy of the Radar Control Systems radar is unusually high for a Diplex modulation. In additon, there is considerable variability in the expected cost of the Gunn oscillator."

The second radar system cost estimate is derived from a more recent report from RCA (Ref. 11). The report was published on work done by RCA for Minicars, Inc. on a U.S. Department of Transportation program. RCA estimated the cost of a Collision Mitigation Radar System complete with cruise control to be $177.00. This production cost figure was based on 100,000 units, 1979 dollars and 1985 technology. The other part of the Collision Mitigation system on the same program included 4 wheel antiskid system provided by Bendix. The Bendix production cost estimate for this antiskid system (Ref. 12) was $115.00 in mid-1979 dollars in a production volume of 300,000 units per year.

RCA's rationale for their price quote is shown below and is taken directly from Reference 11.

"A production cost analysis of the CMS and headway-control system was prepared using RCA's PRICE program (Ref. 12). The system analyzed consists of an FM/SW Ku-band bistatic radar and a three-chip microprocessor controller set (since large production quantities are assumed, VLSI would be implemented) in a metallized weather-tight plastic box. The cost of the velocity and for the cruise control system, integration, and testings are included in the overall production cost figure. The complete CMS and radar cruise control system is estimated to have a production cost figure of $177.00. This production cost figure is based on 100,000 units, 1979 dollars and 1985 technology.

"The PRICE program gives a range of production costs for each item. The upper value is the worst-case prediction. The actual production cost of an item will be somewhere between the high and low extremes. The cost breakdowns are as follows:

"The electronics for the radar and processor are assumed to be contained within a metallized weather-tight plastic box. The box also contains the bistatic radar system consisting of two antennas and associated electronics. The purpose of metallizing the box is to provide a ground plane for the printed circuit antennas. The predicted production cost range of the metallized weather-tight plastic box varies between $12.92 to $18.77, with $15.07 the average cost. The microprocessor system that will provide the CMS and cruise control functions is assumed to require a total of three VLSI clips. The production cost for the three-chip system including the PC board on which the ICs would be mounted ranges from $7.99 to $12.98. The average cost of the three-chip microprocessor controller including the necessary ROM and RAM is $9.58.

"The cost evaluation of the radar system, antennas, transmitter and receiver is based on the use of microwave IC technology. The bistatic antennas are fabricated in PC form. The modulating and analog processing circuitry is assumed to be in IC form. The computed cost range low is $92.67; the maximum cost computed for the Ku-band radar production system is $144.95 with an average of $112.50. An electromechanical solenoid that is used to control the throttle was also estimated by a description of the size and complexity of the device. The PRICE system predicts a cost range between $18.48 and $28.31.

"The steering and speed sensor were the final components of the CMS/headway-control system that were cost evaluated. The speed sensor is described as a device that ouputs a pulse train at logic voltage levels whose frequency is a function of velocity. The steering wheel sensor is a geared potentiometer attached to a steering arm on the front wheel. Based on a description of the function of both sensors and the approximate size of each unit, the sensors have a predicted production cost of $7.06 to $10.89. The assembling of the overall systems and testing is computed by PRICE to be $10.00 per unit.

"The production cost of the complete CMS/headway-control system (excluding braking system) ranges from $147.26 to $228.51. The average $177.00 figure is based on a production run of 100,000 units."

3.5.2 Life Cycle Cost

None of the automotive radar systems is in actual production and, hence, no data is directly available on service life, maintenance and repair requirements, etc. However, experience with the prototypes and radar systems in operation in non-automotive fields indicates that the service life of the automotive radar systems can exceed the life of the vehicle itself. Hence, the repair and maintenance cost should be negligible.

One concern is the damage susceptibility of the antenna itself. Of necessity, it must be mounted on the front of the car. The front portion of the car is very prone to accident-related minor and major damage, and radome housing the antenna is likely to be in the damaged area. However, there is a strong feeling among the radar experts that the antenna could be located inside the passenger compartment on the windshield forward of the rear view mirror, thereby eliminating a number of environmental problems. The cost of the radome and antenna is expected to be about 15 percent of the overall cost of the radar system, and the replacement cost for it is expected to be about $45.

3.5.3 Costs Used in this Study

The radar system costs used in this study are shown later in Section 4. It is believed that the three levels of signal processing used will not have a substantial effect in the corresponding cost estimates since the main difference at three levels lie in the control logic.

It is apparent that the cost of the production is going to be a strong function of the production volume. A general price curve drawn on the basis of production volume and plotted on a log-log scale is shown in Figure 3-13. The data are based on production experience of electronic components and systems of comparable sophistication with automotive radar systems. Figure 3-13 shows the upper and lower bounds of the cost estimates.

3.6 DEVELOPMENT OF ANALYTICAL MODEL AND ITS IMPLEMENTATION

Two separate computer models were developed as a part of this program to analytically evaluate and compare performance of selected radar systems. The first computer model simulated an antenna. The second computer model simulated the target cross-section and the signal processing of the radar systems. Full details of these two models and the analytical effort is contained in Appendix F and G respectively. The following two sections briefly summarize the modeling and analysis efforts.

3.6.1 Antenna Model

3.6.1.1 Block Diagram

Figure 3-14 shows a simplified block diagram of a typical braking system. It is deliberately general in form and must be adapted to each system condsidered. Diagram units are described below.

- Antenna

Several types of antenna can be used in Automotive Radars. The most widespread is the horn- or waveguide-fed parabolic reflector with circular rim shape. Other rim shapes are possible, though uncommon. Parabolas offer the advantage of high directivity and low cost. Horns are sometimes used. Horns are probably the simplest and least expensive antenna, but the trade-off is a lower directivity

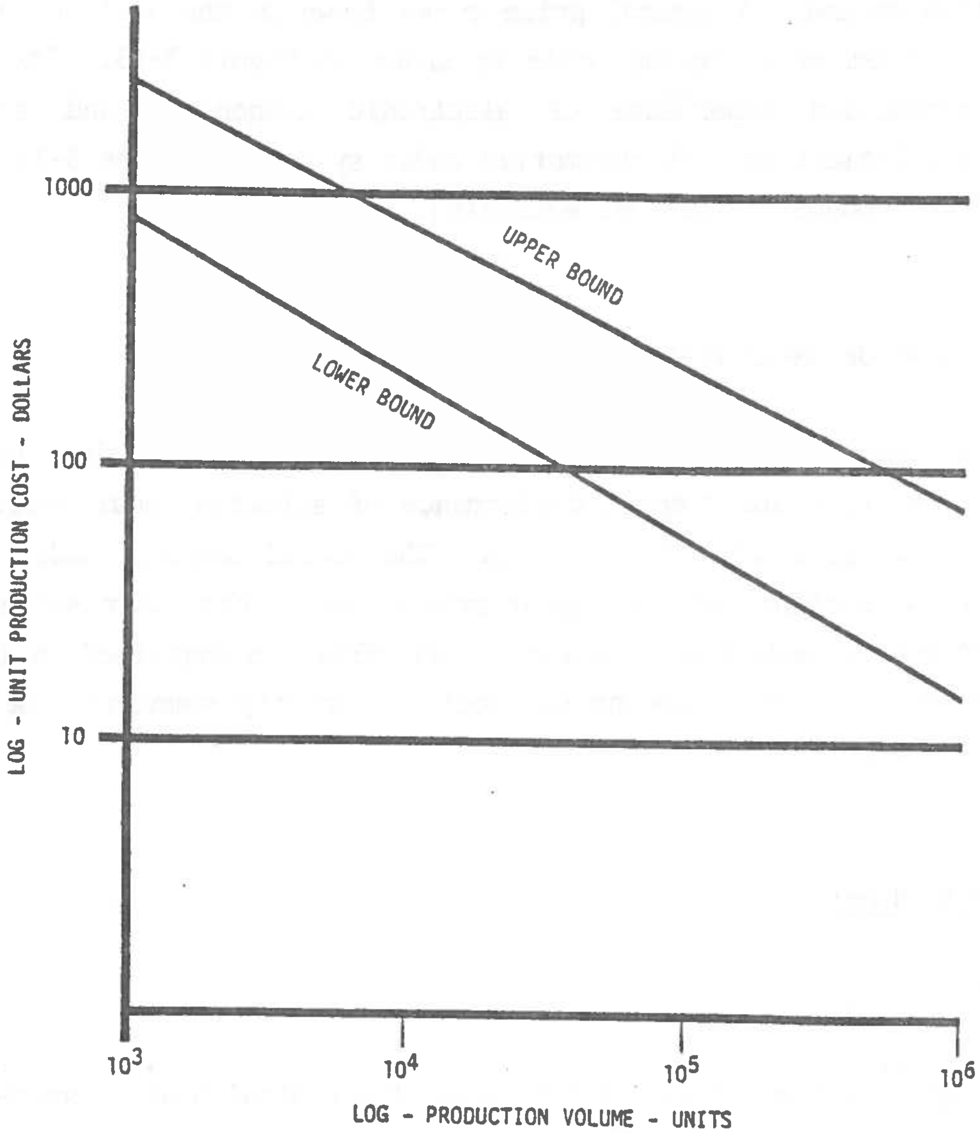


FIGURE 3-13. UNIT PRODUCTION COSTS AS A FUNCTION OF PRODUCTION VOLUME FOR COMPARABLE ELECTRONIC SYSTEMS

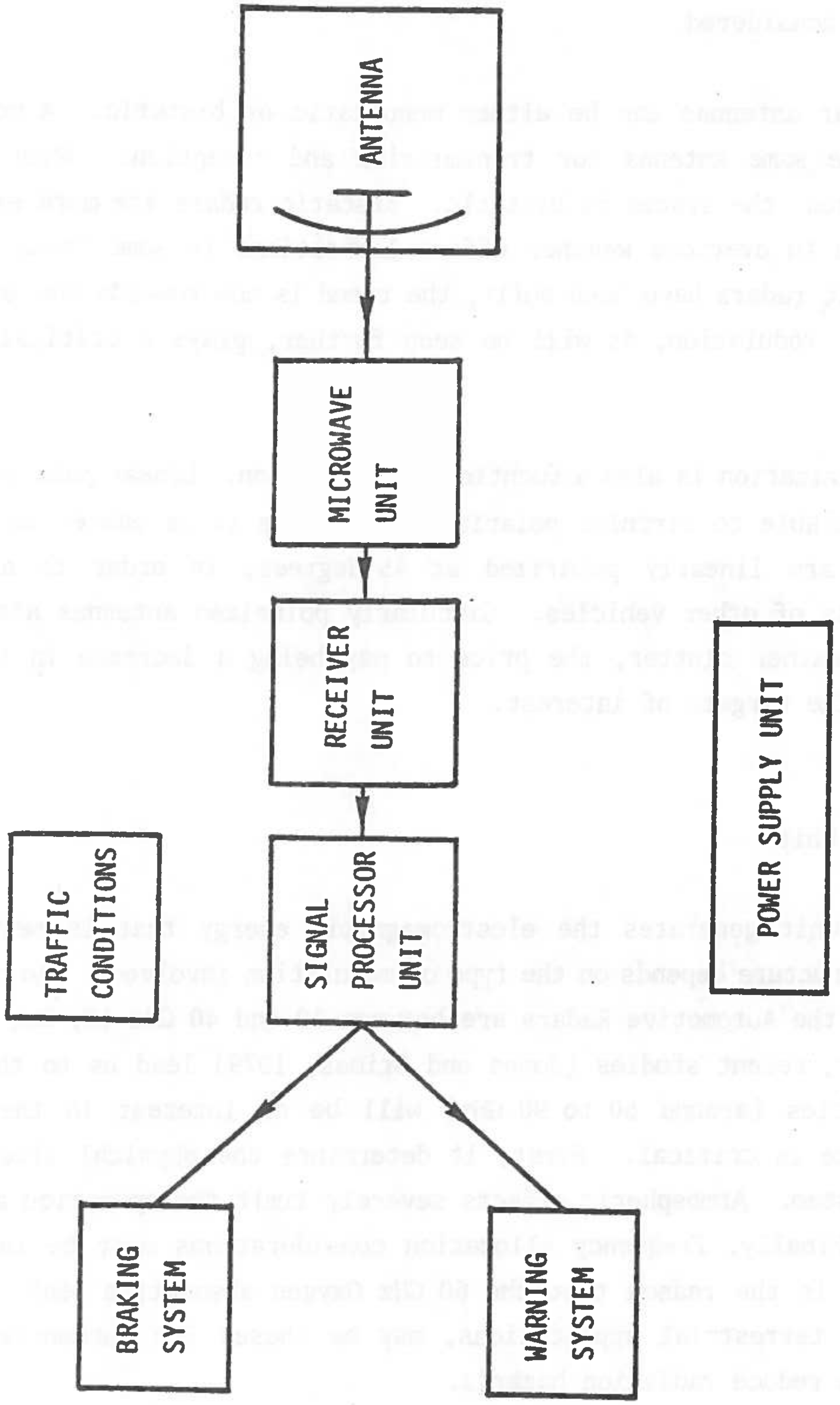


FIGURE 3-14. SYSTEM BLOCK DIAGRAM

and a higher side-lobe level. Arrays, dipoles and printed devices (RCA, 1980) have also been considered.

Automotive Radar antennas can be either monostatic or bistatic. A monostatic system uses the same antenna for transmission and reception. When separate antennas are used, the system is bistatic. Bistatic radars are more expensive, but more suited to overcome weather effect limitations in some cases. Though several bistatic radars have been built, the trend is now towards the monostatic configuration. Modulation, as will be seen further, plays a critical role in that choice.

The chosen polarization is also a fucntion of modulation. Linear polarization is generally preferable to circular polarization because it is easier to achieve. Most antennas are linearly polarized at 45 degrees, in order to avoid the blinding effects of other vehicles. Circularly polarized antennas also reduce blinding and weather clutter, the price to pay being a decrease in the power returned from the targets of interest.

- Microwave Unit

The microwave unit generates the electromagnetic energy that is sent to the antenna; its structure depends on the type of modulation involved. The operating frequencies of the Automotive Radars are between 10 and 40 GHz (X, Ku, K and Ka band). However, recent studies (Jones and Grimes, 1979) lead us to think that higher frequencies (around 60 to 90 GHz) will be of interest in the future. Frequency choice is critical. First, it determines the physical size and the cost of the system. Atmospheric effects severely limit the operation at higher frequencies. Finally, frequency allocation considerations must be taken into account. This is the reason that the 60 GHz Oxygen absorption peak, which is seldom used in terrestrial applications, may be chosen for Automotive Radar. This would also reduce radiation hazards.

Almost all systems consist of a Gunn diode as a main oscillator. The resulting continuous wave is modulated. Various modulations are possible: pulse, pulse Doppler, FM-CW (with triangular, sawtooth or sinusoidal modulation), and DIPLEX (double-frequency). Extraction of the necessary information about the target is performed differently for each principle. In the pulse mode, the continuous wave is modulated by rectangular pulses, whereas more complicated shapes are involved in continuous waves devices. The FM-CW mode requires less peak power, due to the duty cycle equal to unity, but presents more danger of radiation exposure.

- Receiver Unit

The returned signal provides information about target range and target relative velocity.

1. For a pulse-modulated radar, range is determined by measuring the time taken by the pulse to travel and return. Pulse repetition frequency must be chosen so that the maximum unambiguous range is sufficiently large ($\simeq$100 m). The velocity is determined either by measuring range variation with time or measuring the Doppler frequency. Pulse Doppler radars have the ability, as opposed to ordinary pulse radars, to discern moving targets even in the presence of fixed targets producing an echo several orders of magnitude greater.

2. In FM-CW modulation, except for sinusoidal modulation, the relative velocity is obtained from the Doppler frequency. Frequency modulation allows the range to be measured. However, as a beat frequency measurement is performed by counting, a fixed error is introduced. The relative velocity determination is more precise with FM-CW than with pulse radars.

3. Square wave FM-CW system use, for modulation, two slightly different frequencies. Range is extracted in this case by measuring the relative phase of the two Dopplers. The fixed error is eliminated but radial motion is needed to obtain range information from the Doppler signals. This configuration is, therefore, less suited for cruise-control applications.

4. Sinusoidal FM-CW radars do not require radial motion to extract the range, but are more complicated to build. Pulse-modulated radars are often considered as better suited to long-range measurements, whereas the various FM-CW and DIPLEX systems are short-range radars.

- Signal Processor Unit

With the advent of microcomputers, radar signal processing has been noticeably improved. These improvements have been particularly important for the development of Automotive Radar braking systems. The typical auto environment is very complex. In addition to the targets of interest, which are those for which braking or warning must be activated, other non-hazardous targets may produce enough return to generate a "false-alarm." It is clear that the best system will be the one which achieves the best compromise between actual detection of hazardous targets and the false-alarm rate.

The purpose of the signal processing unit is then to determine, from the extracted information, whether or not the alarm will be activated. Basically, signal processing is achieved in three steps: target acquisition, target detection, algorithm analysis. Signal processing units are classified into three groups, depending on the level of sophistication.

The first group consists of the simplest models. The target acquistion is achieved as soon as the returned signal exceeds a given threshold. The detection is automatically ensured. If the algorithm analysis produces a positive result (hazardous target), activation occurs.

However, for the first class of processors, a malfunction may result from the detection of a peak of noise. Processors of the second class overcome this problem. A target is detected only if, after acquisition, signal threshold is exceeded during more than a given interval of time or, alternately, more than a given interval of distance. Acquisition and detection are now two separate steps.

Various algorithms have been developed for the processors of the first two groups. All must include traffic conditions: dry or icy, smooth or rough road surfaces lead to a different maximum admissible deceleration. In addition to this, the carrier vehicle velocity and the steering wheel angle must also be taken into account. In particular, the adjunction of a steering wheel angle coefficient substantially reduces the number of false-alarms occurring on curves.

Systems of the third generation are still in the process of being developed. C.A. Research Corporation is working on a device which involves a more sophisticated algorithm. Acitivation is enabled only when the vehicle is found to be on a collision course, a technique similar to that used by some missile guidance systems. This technique requires subdivision of the vehicle environment in elementary cells, so that a course can be determined and identified.

3.6.1.2 Antenna Modeling

Antenna modeling is the basis of this theoretical analysis of Automotive Radars. Radiation patterns determine the vehicle environment as it is seen by the radar. These patterns must therefore be known with a high degree of accuracy. For instance, the amount of power returned from a stop sign or a guardrail, a non-hazardous target, is directly influenced by the side-lobe level. Simple analytical models turn out to be a very inappropriate representation. This is the main reason that antenna modeling must be developed.

Beyond a confirmation of experimental results, theoretical antenna modeling, associated with target detection simulation, allows target detection to be evaluated for unusual occurrences. Hence, further improvements may be suggested and tested.

The parabolic reflectors are the most commonly encountered type of Automotive Radar antennas. They have, therefore, been chosen to be modeled in this study. Calculations involved in antenna modeling could not have been successfully achieved without the aid of computer programs.

It must be noted that Automotive Radar antennas are operating in very particular conditions. Ground relections, for instance, completely alter the initial antenna pattern. Therefore, the modeling of the antennas would not be thorough if such propagation effects were not studied.

3.6.1.3 Systems Evaluated

Three systems evaluated in the context of this study are shown in Table 3-7.

- Bendix System

This radar is a DIPLEX monostatic device, using a waveguide-fed parabolic antenna ($\theta v = 4^{o}$, $\theta h = 2.5^{o}$). The antenna is polarized at 45 degrees. The operating frequency is 36 GHz $\pm$ 410 kHz. The transmitted peak power is 25 mW. The receiver is a superheterodyne type. Detection is enabled if the returned signal exceeds the threshold on a given distance: 0, 11.5, and 23 feet have been tested. The processing includes steering wheel angle information and uses the following algorithm:

$$R + 2\dot{R} < 0 \quad ,$$

where R is the range to the target and $\dot{R}$ is the range rate.

Dr. Grimes and Dr. Carpenter have had the opportunity to drive, for several months, an experimental vehicle equipped with the Bendix system. Noteworthy information has been found in the technical report issued by Bendix Research Laboratories (Bendix-NHTSA report, Phase II, 1976).

- Nissan-Mitsubishi System

The Nissan-Mitsubishi system is pulse-gated radar, monostatic, operating at 24.15 GHz. The horizontal and vertical antenna beamwidths are equal to 4 degrees. The antenna is a horn-fed parabolic reflector, polarized at 45 degrees. The pulse width is 20 ns and peak power 20 mW. The receiver is a superheterodyne type. The 20 ms pulses are generated by rectangular modulation of the Gunn oscillator continuous wave: the remaining CW waves are shifted 160 MHz from the original frequency and transmitted to the mixer as local oscillator signals. This produces, after mixing, intermediate frequency pulses of 160 MHz. Range information is obtained from the delay time of echo pulses,

TABLE 3-7. SYSTEMS CHARACTERISTICS

Description	Nissan-Mitsubishi	Daimler Benz SEL	Bendix
System			
Principle	Pulse Doppler	FM-CW	Diplex
Range	5-100m	10-100m	30-75m
Accuracy	$\pm$ 1 m	$\pm$ 2.5 m	
Relative Speed	128 km/h	160 km/h	
Accuracy	$\pm$ 1km/h	$\pm$ 2.5km/h	
Antenna			
Number & Type	1 parabola	2 parabola	1 parabola
Beamwidth	H3.5, V4.5	H2.5, V3.5	H2.5, V4
Polarization	45^o	V	45^o
Tx and Rx			
Main Oscillator	Gunn	Gunn	Gunn
Frequency	24.14 Ghz	35 GHz	36 GHz
Output Power	30 mW	30 mW	25 mW
Pulse Width	20 ns		730 ns
Receiver	superheterodyne	homodyne	homodyne
Logics			
Algorithm	$R > V^2/2\alpha + V_1T$	$R > V^2\alpha + V_1T$	$R + 2R > 0$
Steer.w.a.	yes	yes	yes

and the relative velocity is extracted from the Doppler frequency by sensing the polarity change of IF-pulses.

The processing includes a range gate controlled in accordance with the vehicle velocity and steering wheel angle. In the chosen algorithm, the safe distance is defined by:

$$R > \frac{V_1^2}{\alpha} + V_1 T + K ,$$

where: T = driver's reaction time,

V_1 = vehicle speed, and

K = constant.

Further information can be found in a paper issued by Nissan Motors Corporation in collaboration with Mitsubishi (Fujikawa et al., 1979). Dr. Grimes has personally visited the Japanese facilities and has been allowed to test a vehicle equipped with the Nissan-Mitsubishi system.

- Daimler-Benz-SEL System

The Daimler-Benz-SEL rader system has been developed in Germany. Two vertically polarized antennas are used in this bistatic device. Dr. Carpenter, who went to Germany and tested a Daimler-Benz-SEL equipped vehicle, reported that a very similar monostatic radar had been developed by Bosch to replace the bistatic one: VDO, SEL and Bosch all use the same antenna by agreement. The horizontal and vertical beamwidths are 2.5 degrees and 4 degrees respectively. The operating frequency is 35 GHz. The chosen modulation is FM-CW and the receiver is a superheterodyne type.

The processing includes information about road conditions, steering wheel angle, and carrier vehicle velocity. The algorithm law is the following:

$$R > \frac{V_1^2}{\alpha} - \frac{V_2^2}{\alpha} + V_1 T + K \quad ,$$

where V_2 = target velocity.

Target detection occurs only if the threshold is exceeded for more than 0.2 second. The false-alarm rate is reduced by eliminating targets for which relative velocity remains constant with time, such as guardrails. For more information, refer to the trip report written by Dr. Carpenter (private information, 1981) and to the documentation published by the German companies (Hahn, 1980; Dull, 1978).

3.6.1.4 Purpose of this Work

- Analytical Evaluation of Available Systems

The purpose of this study is to provide the necessary information for an analytical evaluation of the three systems described in the previous section of this chapter. The results have enabled Jean-Marc Laugenie to develop an efficient simulation process to test the abilities of the devices described above. This work deals more specifically with propagation systems in Automotive Radars.

The emphasis has been put on antenna modeling considerations. Various models are derived and discussed. Hence, comparison with experimental measurements is made. These models allow the test of most of the possible configurations and offer, therefore, the opportunity to evaluate Automotive Radars other than these considered. Further improvements can also be taken into account, due to the versatility of the computer codes.

Influence of the multipath effects is also considered, so that those can be included in the general simulation program of J.M. Laugenie. In addition to this, various atmospheric perturbations like rain, fog, or snow are modeled, and peformance reduction for each radar is estimated.

- Feed and Antenna

As it has been mentioned above, antenna modeling is deliberately restricted to horn-fed parabolic reflectors. This is the typical configuration encountered in almost all radars and, in particular, in the three systems evaluated. As reflector antennas are considered, the modeling is broken into two parts.

1. Feed Modeling The horn feed was modeled first. A computer program has been written in the course of this study to perform the somewhat tedious calculations involved. This code enables the radiation patterns of any horn, pyramidal or not, to be calculated, and offers various possible outputs. In particular, the program creates, if desired, input files to the General Reflector Code which models a parabola. This results in saving considerable time during the interface between feed and reflector.

2. Parabolic Reflector and Antenna Pattern Once feed patterns are computed, it is possible to model the antenna resulting from the association horn-parabola. Another code, GENREF, written by S.H. Lee and R.C. Ruduck, is used for that purpose. This program is versatile enough to accept practically any input feed pattern for parabolic reflectors with various rim shapes.

- Propagation Effects

As a necessary complement to antenna modeling, other propagation effects are studied and included in the evaulation.

1. Multipath Effects Multipath propagation is characteristic of the complexity of the vehicle environment. Many multipath reflections can be considered. However, only a few can be modeled. Ground reflection has been emphasized because it is a permanent effect and, therefore, it alters permanently antenna patterns. Complete calculations are developed for various types of road surfaces, smooth and rough, dry and wet. Conclusions are drawn and the validity of some commonly made assumptions is discussed. A similar analysis is used for other reflections due to the presence of reflecting surfaces on the shoulder of

the road. The particular case of guardrails is also treated; backscattering from guardrails has been studied by J.M. Laugenie.

2. Atmospheric Particles Atmospheric particles are found to be a serious problem at K-band, where Automotive Radars operate. Basically, limitations orginate from two phenomena: attenuation and backscattering. Models coming from previous meteorological radar analysis are considered, simplified and applied to the present problem. Hence, with the aid of the derived models, the behavior of the three systems in the presence of weather clutter is estimated.

Gunn & East's compilation paper (1954), and the NHTSA-Bendix report have provided noteworthy information on this subject.

3.6.1.5 Conclusion

- Accuracy of the Model

Feed pattern calculations are based on the principles of diffraction theory. The simple model deived exhibits good agreement with experimental measurements. However, the value of the maximum gain, which does not appear on normalized graphs, differs, sometimes noticeably, from the measured values (but generally less than 15 percent). The model is more accurate for determination of normalized patterns, but less suited when the actual value of the gain is to be computed. This limitation mainly affects the modeling of horn antennas without reflectors. If the horn is coupled to a reflector, parabolic in the present case, only normalized patterns should be used as input to the code GENREF. Discrepancies due to normalized feed pattern determinations are less than a few percent.

- Validity of the Assumptions

The validity of the assumptions made during the course of this study depends on the chosen geometry.

Wavefront Distortion The model is less accurate for horns with both small flare angle and aperture dimensions a and b differing by more than two orders of magnitutde. If the values of a and b are too different, there is an important wavefront distortion from the assumed spherical shape. Therefore, phase error in the plane of the aperture is no longer quadratic.

Optimization and Phase Error Optimization of the horn is a delicate problem. A compromise must be found between optimum geometry and the physical limitations of the system, such as aperture blockage. Deviation from optimum geometry leads, in particular, to strong variations of the phase of the E-field. This is especially true at higher frequencies. As GENREF assumes a constant phase error for input feed patterns, discrepancies may results and final patterns may be altered.

- Waveguide Feeds

Waveguide feeds can be seen as the limit case of horns with infinite flare length (or zero flare angle). This is equivalent to neglecting quadratic terms in the integrals. Waveguide feeds have a lower directivity and are poorly matched. This is the reason that horn feeds are usually prefered to waveguides.

- Automotive Radars and Multipath Propagation

Ground Reflections Various models have been derived to describe the effects of multipath reflections on the propagation. The curves plotted have shown that:

1. For low grazing angles, both vertical and horizontal reflection coefficients Rv and Rh are decreasing with increasing angle.
2. The decrease is much steeper for Rv than for Rh.
3. There is an angle for which Rv is zero (smooth model) or nearly zero (rough model). Beyond this pseudo-Brewster angle, Rv increases again towards an asymptotic value.
4. For a dry smooth road, Rh is decreased by 50 percent around an angle of 10 degrees. For a wet rough road, the half point angle is only

5 degrees. Usual road surface parameters can be considered to be between these two extremes. Except maybe for the second case, the phase of Rv can be taken as a constant: $+\pi$ before Brewster angle, 0 beyond.

Considering the geometry of the system, it is obvious that grazing angles of interest in Automotive Radars are generally lower than 5 degrees, 2 degrees being a typical value. For such an angle, the curves show that Rh and Rv are nearly equal to unity. As the phase is equal to π, it is reasonable to assume:

$$Rh = Rv = -1$$

These are the assumptions usually made in low angle radar systems, especially in naval applications. The only exception is the case of very rough road surfaces, such as grooved pavements.

When reflection coefficients are taken equal to unity, a phase shift of $+\pi$ radians is introduced by the reflection. In other words, the signal returned from targets lying in the vicinity of the ground plane is strongly reduced by the destructive addition of direct and reflected rays. For example, a fallen tree or a rock probably will not be detected by the radar. The main effect of roughness or water is to smooth pattern alterations.

<u>Other Multipath Reflections</u> The models derived for ground reflections can be applied to other multipath occurrences, typically, reflections from buildings on the side of the road. From the previous analysis, it is clear that, due to the larger grazing angles, Rh and Rv are much smaller than unity. Therefore, that type of multipath is negligible.

<u>Guardrails</u> A simple way to evaluate perturbations caused by the presence of guardrails is to take the model of a flat metallic plate. Then Rv and Rh are equal to +1. In that case, as targets of interest lie far enough from the plane of reflection, that is to say the vertical plane in which the guardrail is located, pattern alteration is minimized. However, considering the expression giving the phase shift between the direct and the reflected ray, the phase shift due to the path difference, it turns out that this shift behaves as if it were

randomly distributed for the different possible geometries of the system car-guardrail. Fluctuations of the distance car-guardrail produce strong variations of the phase shift. Phase-shift fluctuations produce, in turn, fluctuations in the signal from a target. If the processing of the system does not include the necessary protections against this phenomenon, as range delay, malfunctions may result. However, the effects of the variations are smoothed for complex targets, such as automobiles.

It must be noted that guardrails also produce a partial screening of the side of the road. This cannot be seen as a limitation for Automotive Radars, because it helps reduce the number of false alarms.

- Weather Effects

From the analysis of atmospheric perturbations on the propagation of radar waves, the following conclusions are made:

1. <u>Attenuation</u> The attenuation phenomenon is generally negligible in Automotive Radars. The atmospheric attenuation is very low and rain attenuation becomes perceptible only at higher frequencies (around 50 GHz) and higher rainfall rates (around 40 mm/h). For range lower than 130 m, it is reasonable to disregard attenuation.

2. <u>Backscattering</u> Backscattering effects can be, in some cases, a serious limitation to radar performances. At that stage, the modulation plays a critical role.

Pulse modulated radars, and in particular pulse gated radars, are nearly immune to rain clutter. The clutter power received originates from a small cell surrounding the vehicle. The narrower the beamwidth, the smaller the cell and therefore the less clutter signal returned.

Monostatic FM-CW radars using linear polarization are much more sensitive to weather effects because they receive a continuous flow of radiation from meteorological particles. A consequence is that targets with a small cross-section, such as a bike or a pedestrian, may not be detected in a heavy rain.

A bistatic configuration helps reduce the amount of clutter received, in particular, near-field clutter.

Choosing a circular polarization is an efficient way to work out the problem, but the trade-off is a small decrease of the signal returned from targets of interest. It also helps the blinding problem.

- Systems Evaluation

In light of the previous comments, a comparison can be made between the three Automotive Radars evaluated. An overall evaluation of the systems will be found in Laugenie's thesis, in which a method of simulation for analysis of Automotive Radars is developed. It includes the results of the present study and also target cross-section modeling and signal processing considerations. This enables the performances of each device to be estimated.

Antenna Modeling and Propagation The antenna characteristics of the three systems are very similar, except for the fact that the Daimler-Benz-SEL system, in its original configuration, is bistatic. More precisely, the Japanese radar beamwidth is slightly smaller than that of the other two. The effect of such a small variation can only be evaluated during the simulation process. However, it must also be noted that the Nissan-Mitsubishi antenna has a very low side-lobe level.

All antennas are linearly polarized. Nissan-Mitsubishi and Bendix have chosen 45 degree polarization, whereas the German bistatic system uses vertical polarization. The latter is therefore more sensitive to a possible blinding from other vehicles.

Modulation and Frequency Daimlar-Benz-SEL and Bendix radars operate at approximately the same frequency (around 35 Ghz). The Nissan-Mitsubishi systems uses 24.15 Ghz.

The chosen modulations are the following:

a)	Nissan-Mitsubishi:	Pulse-gated
b)	Bendix:	Diplex
c)	Daimler-Benz-SEL:	FM-CW

From these data and from the previous analysis, it appears that the Nissan-Mitsubishi system is the most efficient in the presence of atmospheric perturbations because of the pulse modulation and the gating of the receiver. The German system is less immune to rain, in particular, in its monostatic configuration. The Bendix Diplex system is similar to the Daimler-Benz-SEL, since it is also a continuous wave device. The monostatic configuration is again a limitation in bad weather, but it would be unwise to claim that FM-CW radars should be rejected because of their sensitivity to rain clutter. Other considerations which are not discussed in this study have to be taken into account, such as the precision of the measurements. These factors are discussed in the next section.

3.6.2 Target Modeling

A computer model is developed that describes the variations in the radar cross-sections of complex bodies, such as cars and road signs. This model simulates a complex target by combination of rectangular flat plates. It is used to evaluate the probability of detection and the probability of false alarms for selected radar systems currently under development

Definition of terms used in target detection and random variation of cross-sections is explained below.

3.6.2.1 Target Detection

- **Definition of Parameters**

Range Cut-Off: "RCO" In most of the systems, a Range Cut-Off "RCO" is defined,so that no target beyond this range can be detected by radar. It is the easiest way to reduce the number of false alarms, by suppressing the echos from large remote obstacles.

A velocity-dependent Range Cut-Off can easily be set for pulse radar, by varying the pulse modulation frequency with the carrier vehicle velocity. It is also an attractive way to account for the increase of safe stopping distance.

Some systems provide a modified Range Cut-Off on curves: radar detection on curves is limited to a shorter distance, depending on the steering wheel angle. This should be effective in preventing detection of guardrails or trees on the roadside.

Detection Threshold: "STH" Basically, a target is detected when the signal returned to radar exceeds a certain threshold, which needs to be defined. This threshold can either be constant, or depend upon several parameters, such as carrier velocity, steering wheel angle, weather conditions (fog). A velocity-dependent threshold allows earlier detection of targets at high speeds, hence, increasing collision avoidance efficiency. On the other hand, steering wheel angle dependence seems inappropriate: range detection must be shortened on curves, to avoid detection of sideroad obstacles, but capacity of detection must remain the same in the vicinity of the carrier vehicle.

Radar Delay: "Tdel" or "Rdel" A radar delay is set to avoid detection of short peaks of noise. Once the detection threshold "STH" defined above is exceeded, there is acquisition of the target; detection of the target occurs only if the returned signal remains above the threshold during a certain period of time "Tdel". This period of time can be defined either as a constant or as the time necessary for the carrier vehicle to cover a fixed distance "Rdel". In the first case, the parameter is called Radar Time Delay, noted "Tdel", while in the second case it is called Radar Range Delay, and noted "Rdel."

A Radar Time Delay is, in general, more efficient at low speeds than at high speeds, because the distance covered between the processes "acquisition" and "detection" increases with velocity. Nevertheless, it still gives fairly good results up to 60 or 70 mph, lowers the false-alarm rate, and is simple to generate.

Activation Time: "Tact" It is a time delay corresponding to the method of activating brakes; if brakes are automatically applied, it can be quite short, and even negligible; if brakes are manually applied, as in the German system (the driver himself, warned by an alarm, activates the brakes), then this delay can be much longer, and an average value must be chosen as the mean driver reaction time.

Braking Decleration: "Brd" This depends mainly on the driving conditions: "Brd" can vary from 0.15g (g 9.81 m/sec) for an icy road, to 0.7g for a dry road. An anti-lock system can significantly improve the braking efficiency (+15 percent) on icy roads, but not on dry roads. Nevertheless, an anti-lock system offers vehicle stability, which is a major accident prevention factor.

Radar Control Law: "RCL" Assuming a target has been acquired and detected, it must be determined whether the brakes are to be activated or not. An algorithm is used to compute the minimum safe distance and to decide if the target is hazardous. It can involve various parameters, in particular, range and range rate (relative velocity), but also braking deceleration and carrier vehicle velocity.

As soon as the target has been detected, this Radar Control Law is checked, and an alarm is set (optionally, brakes are applied) if the target is hazardous.

A more elaborate algorithm can be used, involving the target "past life", and predicting its trajectory. A microprocessor can memorize the location of a few targets at several instants, and determine whether any of these targets is on a collision trajectory; it could also possibly memorize the signature of certain well-known false targets, such as guardrails or bridges, and compare the signal to these signatures. Non-hazardous targets could be partly eliminated this way, so it would signifcantly reduce the number of false-alarms.

- Random Variation of Cross-Sections

Probability of Detection The cross-section of a complex body, such as a car, fluctuates very quickly with time, so the target modeling, using flat plates actually gives an average value. These fluctuations are well-represented by a Rayleigh density function f (Skolnik, 1962).

$$f(\sigma) = \frac{1}{\sigma_{av}} \exp\left[\frac{-\sigma}{\sigma_{av}}\right]$$

The relative power "Srel", computed by the program, is proportional to σ; therefore, the probability density function for the returned signal "S" is also a Rayleigh function:

$$f(s) = \frac{1}{Sav} \exp -\left[\frac{S}{Sav}\right] ,$$

where Sav is the average relative signal computed by the program.

Then the probability of detecting the target at the instant t is:

$$p\left\{ Srel > Sth \right\} = \int_{S_{th}}^{\infty} \frac{1}{Sav} \exp\left[\frac{-Srel}{Sav}\right] \bullet dSrel \quad .$$

This gives the final result:

$$P\left\{ Srel > Sth \right\} = \exp\left[\frac{-Sth}{Sav}\right] .$$

This shows that an important error would be made if it was assumed that the target is detected as soon as Sav = Sth (when Sav = Sth, the target has a probability of being detected $p \simeq 0.36$).

Cumulative Probability of Detection Given that a target at a range R has a probability of being detected p(R) as computed above, the problem now is to determine its probability of being detected at or before R; it will be noted "P", and called "Cumulative Probability of Detection."

In the program used for this simulation, the relative signal, S, is computed at discrete ranges, Rk, where R1 is the range cut-off. Assuming the events are independent (Larsen Shuber, 1979), the probability of not being detected at or before Rk is:

$$Q(Rk) = 1 - P(Rk) = \prod_{k} [1 - p(Rk)] \quad .$$

This gives

$$P(Rk) = 1 - \prod_{k} [1 - p(Rk)] \quad .$$

Q(Rk) is related to Q(Rk - 1) by the relation:

$$Q(Rk) = Q(Rk-1) \bullet [1 - p(Rk)] \quad .$$

Hence, the final result is:

$$P(Rk) = P(Rk - 1) + [1 - P(Rk - 1)] \bullet p(Rk) \quad .$$

This relationship will be used in the program to compute the cumulative probability of detection at range Rk. Then, it will be assumed that detection occurs at a range Rn where $P(Rn - 1) < 0.99$ and $P(Rn) > 0.99$.

The assumption concerning the independence of the events is true if the difference Rk - (Rk - 1) is greater than the average target correlation distance, which is very difficult to evaluate. However, computations are performed at every meter, which seems a reasonable correlation distance.

3.6.2.2 Results and Conclusions

The detailed results of the analytical study are fully presented in Appendix G. Some of the conclusions are presented here as a summary of the results.

The model developed in this study provides relative results, which need to be interpreted. Its accuracy depends mainly on the chosen representation of the targets: dividing a given target into a large number of flat plates does not necessarily increase the accuracy of the results, since the dimensions of each plate must remain large compared to one wavelength. Moreover, it can significantly increase the computation time. A compromise must be found, so that the shape of a target is well represented, with a minimum number of plates.

As previously stated, since no ideal flat plate can be found in the usual environment of a car, the magnitude of the returned signal cannot be accurately predicted. However, the relative variations are quite reliable and the shape of the relative power returned obtained here corresponds fairly well to the experimental data recorded by NHTSA.

The evaluation of the Detection Capacity Rate "DCR" is possible with this model, given certain statistical data. The most common "potential false targets" must be determined and modeled; the average occurrence of these false targets must be known. Indeed, the present definition of "DCR" makes it very difficult to theoretically estimate: if the number of potential (true) targets is approximately 100, the number of false alarms can be evaluated only when the number of potential false targets is known, and this statistical quantity is difficult to predict theoretically.

This model succeeded in accurately predicting the performances of the Nissan system, experimentally tested to this point; it also simulated the lack of precision of the Bendix system Radar Control Law. It can be deduced from this study that the Nissan system probably uses a range cut-off shorter than 400 feet: indeed, a very low false-alarm rate was experimentally observed, while the computer simulation shows that a 400-foot Range Cut-Off will give rise to many false alarms.

SECTION 4
COLLISION AVOIDANCE SYSTEM BENEFIT EVALUATION

4.1 INTRODUCTION

The primary objective of Contract No. DTNH22-80-C-07530, "Collision Avoidance System Cost Benefit Analysis," is to conduct a realistic and rigorous cost-benefit analysis for various radar collision avoidance systems. Earlier reports (Refs. 7, 14, 15, and 16) have documented the selection of a methodology and accident data base for use in the analysis.

The results reported in this section are obtained from the analytic reconstruction of year 1979 North Carolina motor vehicle accidents including 248,536 vehicles. Analysis is performed by the Radar Brake Algorithm which reads cases from a data file of motor vehicle accident involvements, traces the vehicle trajectories according to accident geometry and traveling and impact speeds of the vehicles, considers at what time or if a radar controlled brake system would have applied vehicle brakes, and computes the relative or closing velocity at impact both for the actual case and for a radar brake modified case. The values of relative velocity at impact, Vrel, are tabulated in 5 mph increments of velocity for each of several impact configurations for each vehicle. Separate distributions are obtained from each radar brake system studied and for a no-radar baseline case. Further, separate distributions can be obtained according to the types of vehicles involved in the accident (e.g., passenger car, truck, etc.).

The relative velocity distributions are used as input data to the Kinetic Research Accident Environment Simulation and Projection (KRAESP) Model (Refs. 17 and 18) which predicts the number of injuries and fatalities that would occur in accidents occurring at the specified relative velocities. KRAESP uses the Vrel data together with nationally representative vehicle population data to compute a crash severity measure for each accident. Currently, vehicle velocity change (Delta-V) is the variable used. This is obtained from Vrel via the transformations:

$$\Delta V_1 = \frac{M_2}{M_1 + M_2} \text{Vrel} \qquad \text{Vehicle-to-Vehicle}$$

$$\Delta V_1 = \text{Vrel} \qquad \text{Fixed Object}$$

where M_1, M_2 are vehicle masses.

Once the crash severity is known, the distribution of injuries by values of overall injury severity (AIS) is obtained from statistical relationships of injury severity to crash severity (Delta-V) which have been obtained from the National Crash Severity Study (NCSS) file and input to the KRAESP Model. The calculations take into account crash configuration (vehicle-to-vehicle front, side, and rear; fixed-object front and side; and rollover or non-collision), seat position, vehicle type, and the effects of restraint usage.

The Radar Algorithm itself predicts pedestrian injuries and property damage losses for the modified accidents. These predictions are based on relationships between pedestian injury or property damage and Vrel which have been obtained from the North Carolina accident data itself. The derivation of these relationships is detailed in Appendix H.

The radar systems considered include four different radar system control laws (Systems 2-5) and a no-radar baseline system (System 1). The radar operates by applying full vehicle braking when it sees a sufficiently hazardous situation. A description of the radar system properties and control algorithms is found in Section 4.3 and Appendices I and J. The current evaluation is of a fully automatic collision avoidance and mitigation radar system. Such a system operates without any driver-required input, and activates braking only when any further delay in doing so would probably result in a serious accident. The benefit of this type of system would be primarily in cases of driver inattention or slow reaction (for example, rear impacts). The effects of substantial brake activation time delays which might correspond to driver response to a warning system have also been investigated (Section 4.4).

The outcome of the analysis is a tabulation of accident involvements avoided, property damage loss reduction, and reduction in the number of fatalities and injuries as a consequence of the actions of the radar brake system. Table 4-1 presents a summary of the results for each of the four control laws examined. As would be expected, the largest relative benefit is in rear impact involvements,

TABLE 4-1. SUMMARY OF BENEFITS FOR RADAR SYSTEMS SHOWING THE NUMBER AND PERCENT OF INJURIES, ACCIDENTS AND PROPERTY DAMAGE AVOIDED

Radar System Two[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
ROF	710	11	1.4	16	367	12	151	17	58	17	9	16	7	20	10	18	602	14
ROS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ROLL/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	6,270	19	3.9	17	2,042	18	310	17	105	18	93	19	7	23	23	24	2,509	18
VVS	1,122	4	1.1	6	363	4	40	3	30	3	5	3	2	3	6	3	446	4
VVR	2,664	53	1.2	51	1,380	56	65	60	29	67	7	58	2	100	19	76	1,493	56
Ped[4]	487	14	0.2	15	239	13	65	14	43	14	12	15	5	15	42	26	406	14
Total	11,253	7.8	13	12	4,392	14	632	11	256	9	54	10	23	10	100	13	5,457	13

[1] Defined by the control law $R_B = 2\dot{R}$.

[2] Includes accidents with AIS = 0 injuries.

[3] In millions of dollars.

[4] Tabulated for unmodified Vrel.

TABLE 4-1. (Cont'd)

Radar System Three[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	73	1	1.0	10	149	5	134	15	49	15	9	16	7	20	10	18	358	8
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roll/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	4,802	15	3.4	15	1,612	14	251	14	88	15	19	17	6	19	21	22	1,997	14
VVS	1,084	4	.8	4	356	3	40	3	29	3	5	3	2	3	6	3	438	3
VVR	1,291	26	.7	29	749	30	41	38	14	47	4	33	1	50	16	64	825	31
Ped[4]	419	12	.1	13	202	11	56	12	38	13	10	13	4	12	41	25	351	12
Total	7,669	9	5.9	9	3,032	9	523	9	218	8	47	9	20	9	94	12	3,934	9

[1]Defined by the control law $R_B = \dot{R}^2/2\mu g + \tau\dot{R}$.

[2]Includes accidents with AIS = 0 injuries.

[3]In millions of dollars.

[4]Tabulated for unmodified Vrel.

TABLE 4-1. (Cont'd)

Radar System Four[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	73	1	1.0	10	148	5	134	15	49	15	9	16	7	20	10	18	357	8
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roll/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	6,018	18	3.5	15	1,884	16	268	15	83	14	15	13	5	16	15	16	2,270	16
VVS	791	3	.6	3	238	2	24	2	17	2	3	2	1	2	4	2	287	2
VVR	3,117	62	1.4	59	1,553	63	70	65	21	70	8	67	2	100	18	72	1,672	63
Ped[4]	462	13	.1	14	225	12	62	13	41	14	11	14	5	15	42	26	386	13
Total	10,561	12	6.6	10	4,050	12	559	9	211	7	46	9	20	9	89	11	4,975	12

[1]Defined by the control law $R_B = V_1^2/2\mu g - V_2^2/2\mu g + \tau V_1$.
[2]Includes accidents with AIS = 0 injuries.
[3]In millions of dollars.
[4]Tabulated for unmodified Vrel.

TABLE 4-1. (Cont'd)

Radar System Five[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
ROR	73	1	1.0	10	149	5	134	15	49	15	9	16	7	20	10	18	358	8
ROS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roll/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	6,255	19	3.8	17	2,001	17	298	16	100	17	20	17	6	19	21	22	2,496	17
VVS	791	3	.6	4	237	2	23	2	17	2	3	2	1	2	4	2	285	2
VVR	3,117	62	1.4	59	1,553	63	70	65	21	70	8	67	2	100	18	72	1,672	63
Ped[4]	479	13	.2	15	234	12	64	14	42	14	12	15	5	15	43	26	400	14
Total	10,715	13	6.9	11	4,177	13	590	10	229	8	52	10	21	9	96	12	5,165	12

[1]Defined by the control law $R_B = V_1^2/2\mu g \pm V_2^2/2\mu g + \tau V_1$ (+ for head-on; otherwise -).
[2]Includes accidents with AIS = 0 injuries.
[3]In millions of dollars.
[4]Tabulated for unmodified Vrel.

followed by frontal impacts - both vehicle-to-vehicle and fixed object. The absolute benefits are mainly in the vehicle-to-vehicle front mode due to the large number of accidents in that mode. Interestingly, the greatest benefits regarding fatalities (fatalities are coded as AIS 6) occurs in the pedestrian and vehicle-to-vehicle rear modes. The benefits for pedestrians must be considered to be hypothetical, in that the radar system is assumed to be capable of seeing pedestrians. Expert opinion indicates that state-of-the-art radar systems are capable of detecting pedestrians, but only at unacceptably high false alarm rates. (Radar systems which see pedestrians directly in front of them will also see vehicles and objects in adjacent lanes.)

There is a small but definite tendency for the benefits to be greater for more severe injury categories. This reflects the reduction in severity of accidents which are not avoided. Most of the benefit is obtained from the avoidance of accidents rather than from the mitigation of accidents. This may be substantiated by comparing the relative benefits at the different injury levels to the relative benefit in accidents avoided.

The reader should understand that the terms "involvements" or "impacts" refer to individual vehicles. In a two-car crossing collision there are, therefore, two involvements - one a front impact and the other a side impact. The Vrel is the same for both vehicles. The lack of strong effects in vehicle-to-vehicle side impacts indicates not only a lack of effective radar operation to the side for vehicles hit from the side, but also a lack of effective radar operation for vehicles hitting crossing vehicles. The results for vehicle-to-vehicle front impacts reflect front-to-front, front-to-side, and front-to-rear events. This form of the tabulation is inherent in the KRAESP Model and has been followed consistently throughout the rest of the analysis except for certain parts of the accident trajectory algorithm.

Section 4.2 of this report references the preparation of the North Carolina accident data. Section 4.3 documents the Radar Brake Algorithm itself. Results of the computations and projections obtained from the KRAESP Model are presented in Section 4.4. Section 4.5 contains a discussion of the trade-off between false alarms and missed targets. Section 4.6 discusses the anti-skid systems. Section 4.7 contains the possible cost sharing of radar systems with other electronic hardware. Section 4.8 shows the results of the future benefits, and Section 4.9 presents the supplementary hardcopy analyses. Details of the data handling, program listing, and the other supporting material are contained in the appendices.

4.2 DATA PREPARATION

Computer implementation and preliminary analysis of the 1979 State of North Carolina Accident Data have been reported previously (Ref. 11). In that report it is seen that the North Carolina data are reasonably complete and error free. At the same time it is shown that North Carolina accidents may not be a good representation of national experience due to the more rural character and higher travel speeds involved. A simple adjustment procedure has been implemented for the North Carolina file. This adjustment involves the use of statistical case weights to reproduce the same distribution over speed limits in North Carolina as is found in NASS. The details of this adjustment are documented in Reference 9, which is included in this report as Appendix D.

For the purposes of the present analysis, a case vehicle file of 248,536 involved vehicles has been formed. An analysis file containing these vehicle cases has been prepared under the name CASEWT.DAT and is stored on Tape #1181. Records in this file have the format: ACCIDENT DATA:VEHICLE ONE DATA:VEHICLE TWO DATA

Each vehicle found in the North Carolina file in accidents involving not more than two vehicles is written out to a separate record along with accident and other vehicle information. A listing of the program which reads the North Carolina cases from magnetic tape and writes file CASEWT.DAT is attached as Appendix K. Not all the data items contained in the original implemetation of the data are retained in CASEWT.DAT. The listing in Appendix K may be referenced for further details.

Accidents involving three or more vehicles (5.06 percent of overall data) are not included in the database for analysis because the data available do not include information on the sequence of events, making rigorous analysis extremely difficult.

4.3 RADAR BRAKE ALGORITHM

4.3.1 Overview

The Radar Brake Algorithm is a program which reconstructs individual case vehicle accident involvements in order to account for the effects of automatic radar braking. Figure 4-1 is a summary flowchart of the program structure. The major components of the program are:

- Input data file;
- Program MAIN;
- Two accident classification subroutines, CLASS and MODE;
- Two calculation subroutines, BRAKE and RADAR; and
- Output data file.

The input data file contains one record for each accident involved vehicle. Each data record contains information about the accident, the involved vehicle, and the "other" vehicle, if there is one. In the present case the input data are from the 1979 State of North Carolina accident files but include only accidents involving one or two motor vehicles. It may be noted that the term "vehicle involvement" can include a pedestrian, bicycle, moped, etc. The North Carolina data collection system admits all involved entities as a traffic unit or "vehicle."

The accident classification subroutines CLASS and MODE assign each involved vehicle to categories according to three different criteria. The first is the KRAESP accident configuration. The accident configurations are based on vehicle damage area and other object type. The categories are (1) fixed-object front impact, (2) fixed-object side impact, (3) rollover/non-collision, (4) vehicle-to-vehicle front impact, (5) vehicle-to-vehicle side impact, and (6) vehicle-to-vehicle rear impact. It is assigned to each vehicle here so that the Vrel distributions will be properly categorized for input to the KRAESP Model. The second classification provides a simplified description of the accident geometry. The six possible categories are (1) head-on, (2) rear-end, (3) fixed-object, (4) right-to-left crossing (5) left-to-right crossings, and (6) a null

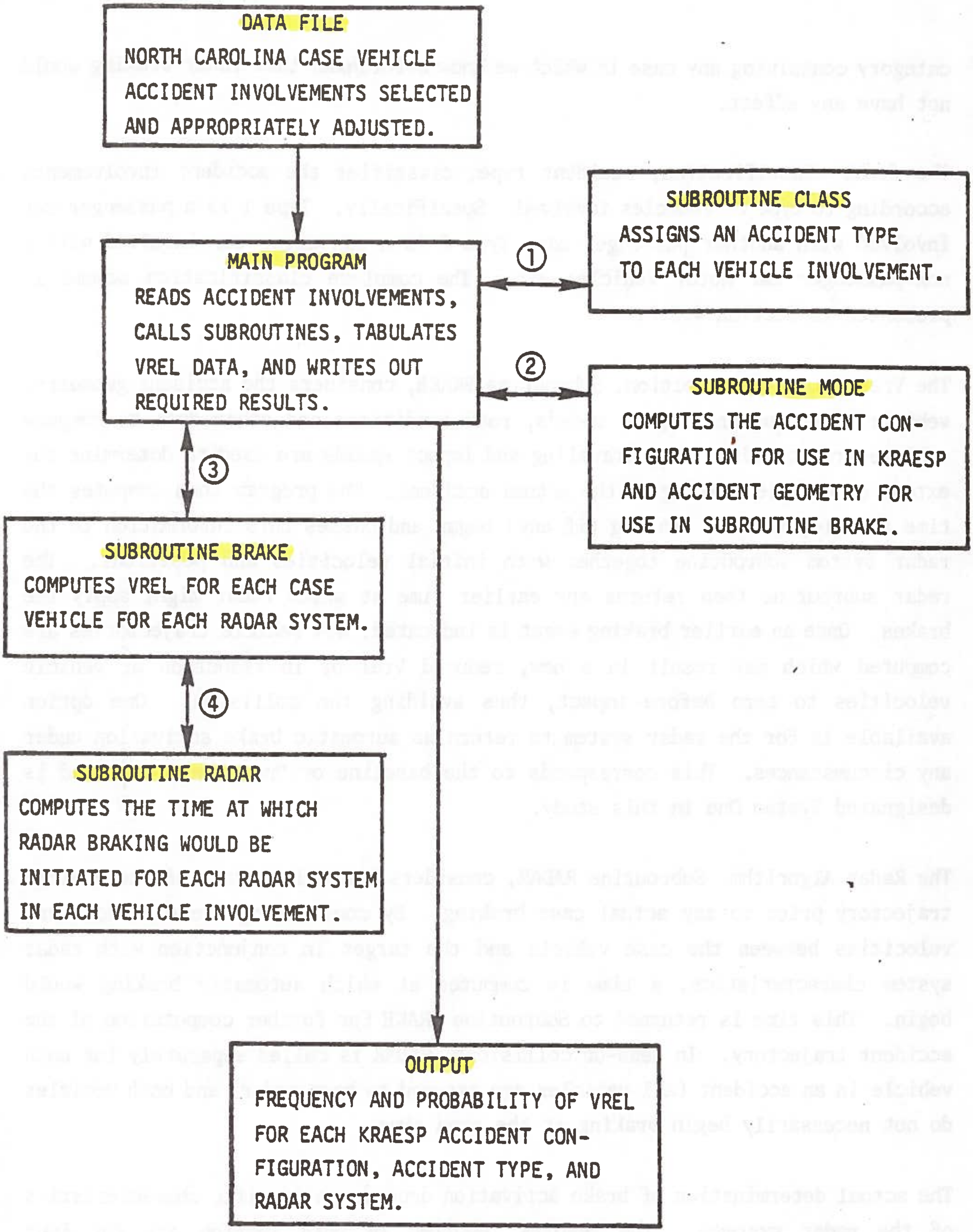


FIGURE 4-1. SUMMARY FLOWCHART OF RADAR BRAKE ALGORITHM

category containing any case in which we know beforehand that radar braking would not have any effect.

The final classification, accident type, classifies the accident involvements according to type of vehicles involved. Specifically, Type 1 is a passenger car involved with another passenger car; Type 2 is a passenger car involved with a non-passenger car motor vehicle; etc. The complete classification scheme is presented in Section 4.3.3.

The Vrel calculation section, Subroutine BRAKE, considers the accident geometry, vehicle traveling and impact speeds, road conditions and other data to compute vehicle trajectories. The traveling and impact speeds are used to determine the extent of vehicle braking in the actual accident. The program then computes the time at which vehicle braking (if any) began and passes this information to the radar system subroutine together with initial velocities and positions. The radar subroutine then returns any earlier time at which radar might apply the brakes. Once an earlier braking event is indicated, new vehicle trajectories are computed which may result in a new, reduced Vrel or in reduction of vehicle velocities to zero before impact, thus avoiding the collision. One option available is for the radar system to return no automatic brake activation under any circumstances. This corresponds to the baseline or "no radar" case and is designated System One in this study.

The Radar Algorithm, Subroutine RADAR, considers those intervals of the vehicle trajectory prior to any actual case braking. By considering the distances and velocities between the case vehicle and the target in conjunction with radar system characteristics, a time is computed at which automatic braking would begin. This time is returned to Subroutine BRAKE for further computation of the accident trajectory. In head-on collisions, RADAR is called separately for each vehicle in an accident (all vehicles are assumed to have radar) and both vehicles do not necessarily begin braking at the same time.

The actual determination of brake activation depends on specific characteristics of the radar systems. The results reported in this section are for four different radar control laws. The radar charcteristics are represented to the model in the form of a relationship between target distance and vehicle speeds which represents a threshold for radar activation. The details of this criterion are discussed in detail in Section 4.3.6

4.3.2 Program MAIN

The purpose of Program MAIN is to read in the accident data, to call appropriate subroutines, to tabulate the Vrel distributions obtained, and to estimate the property damage and pedestrian injury for the modified accident. In addition, Program MAIN writes out data files and case information as required. Figure 4-2 is an overview flowchart of Program MAIN.

The flow of the program is straightforward except for one consideration. Subroutine BRAKE need only be called once for each accident, since Vrel is the same for both cars. However, in the event that the KRAESP accident mode, KSPTYP, is unknown or the brake algorithm configuration, CONFIG, is null for the first vehicle, then it may still be possible to recover a value of Vrel and consider the effect of radar for the first vehicle if KSPTYP is known and CONFIG is not null for the second vehicle. A typical instance of this is the front to rear impact where vehicle one is the rear impacted vehicle. In this case, no effects of radar will be allowed since the case vehicle has no rear-looking radar. Of course, radar on vehicle two will be effective, but the results will not be computed until vehicle two is considered. Program MAIN provides for Subroutine BRAKE to be called for the second vehicle in this case, and the old value of Vrel for vehicle one is replaced with the new one. A second possibility is that the accident geometry may be unclear from the point of view of the first vehicle, due to missing data in the vehicle record, but KSPTYP and CONFIG are obtainable for the second vehicle. In this case, Subroutine BRAKE is called a second time to at least allow data for vehicle two to be included. Normally, the brake algorithm will return the unknown value (999) for Vrel if KSPTYP=8 (unknown) and will not call the radar computation if CONFIG=NULL.

The Vrel frequency distribution is a function of 5 mph Vrel categories (1-5, 6-10, etc.), of the KRAESP accident modes (KSPTYP), of the accident types (ACCTYP), and of the radar system type (SYSTYP). It is computed from the formula

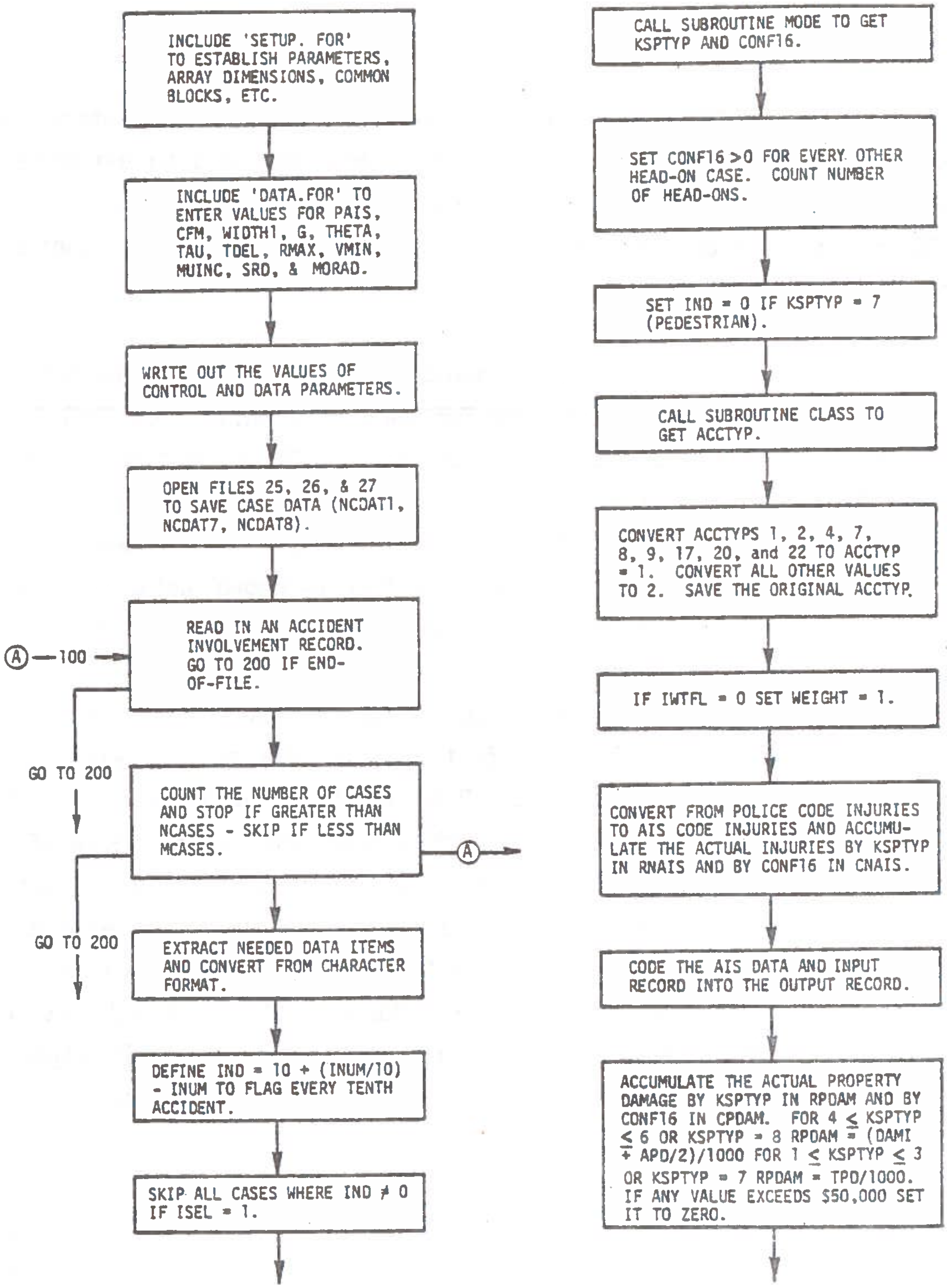


FIGURE 4-2. OVERVIEW FLOWCHART OF PROGRAM MAIN

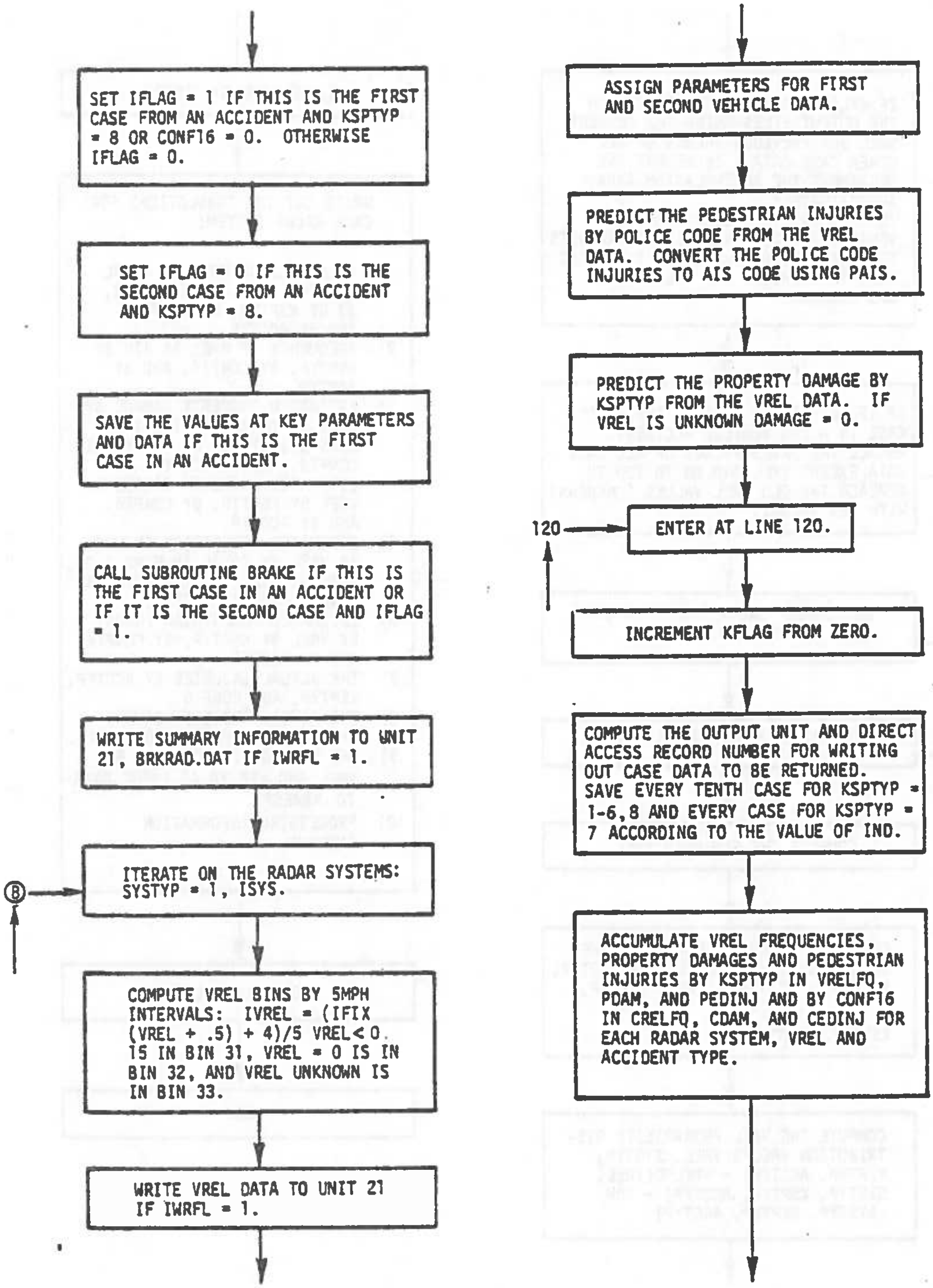


FIGURE 4-2. (Cont'd)

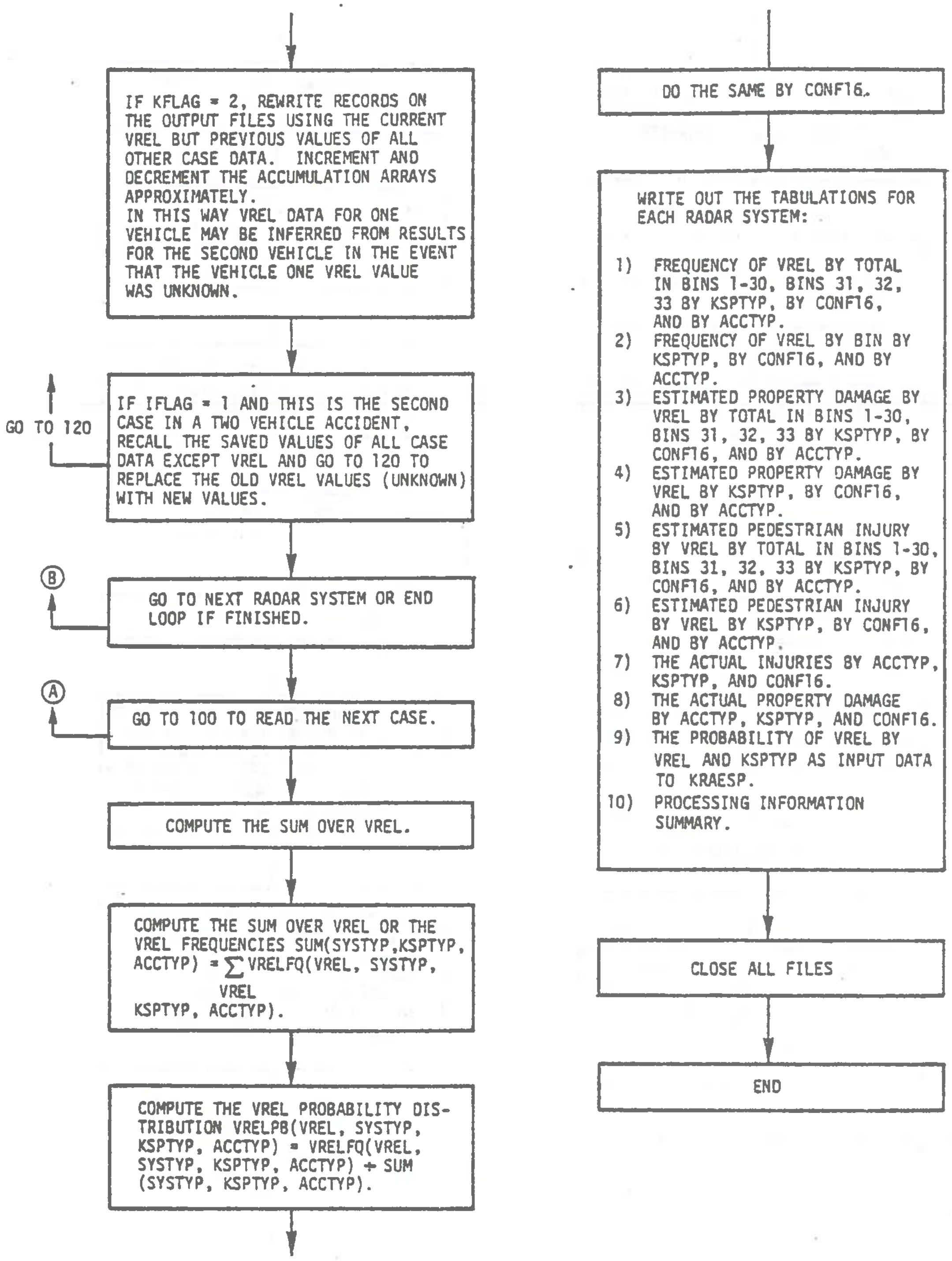


FIGURE 4-2. (Cont'd)

$$\text{VrelFQ(Vrel,SYSTYP,KSPTYP, ACCTYP)} = \sum_{\text{CASES}} \text{WEIGHT}_{\text{CASE}} \qquad (4\text{-}1)$$

(for the given Vrel, SYSTYP, KSPTYP, and ACCTYP)

WEIGHT is the case weighting variable determined from the adjustment of North Carolina to NASS proportions by speed limit.

The Vrel probability distribution is computed from the frequency distribution by the formula

$$\text{VrelPB(Vrel,SYSTYP,KSPTYP,ACCTYP)} = \text{VrelFQ(Vrel,SYSTYP,KSPTYP,ACCTYP)} \div \sum_{\text{Vrel}} \text{VrelFQ(Vrel,SYSTYP,KSPTYP,ACCTYP)} \qquad (4\text{-}2)$$

The probability distribution is a conditional probability contingent on given values of radar system type, accident type, and KRAESP mode. It is normalized over cases having known Vrel (Vrel bin = 1 to 30).

For purposes of the present study, all cases involving a passenger car case vehicle were considered as ACCTYP=1. All other cases were considered as ACCTYP=2. This was accomplished by reducing the values of ACCTYP obtained from SUBROUTINE MODE by the transformation:

1,2,4,7,8,9,17,20,22 ⟶ 1
all others ⟶ 2

In order to preserve case data for additional analyses the following variables were written out to files NCDAT1.DAT (KSPTYP=1-6), NCDAT7.DAT (KSPTYP=7), and NCDAT8.DAT (KSPTYP=8) (according to the format shown):

Original Input Record	A114
AIS Coded Injuries	7F6.3
ACCTYP	I6
KSPTYP	I6
CONFIG	I6
Vrel and Vrel bin by modified and unmodified form by radar system	5(2(F6.3,I6)

These files are further processed by Program CONVERT to rewrite the data into a sequential rather than direct access file. The final output data files are KDAT.DAT (KSPTYP=1-6), PDAT.DAT (KSPTYP=7), and UDAT.DAT (KSPTYP=8).

4.3.3 Subroutine CLASS

This subroutine assigns an accident type to each accident involvement according to the type of vehicle involved and the object contacted. The purpose of this classification scheme is to separate vehicles that have radar installed (passenger cars) from those that do not (trucks, buses, etc.) and to allow for the possibility of special studies of radar brake systems in particular instances. Figure 4-3 is a decision tree flowchart for Subroutine CLASS.

The classifications used are listed in Table 4-2. The variables used to obtain the classifications are:

Vehicle Type:
- Passenger Cars
- Other Type Vehicles (Trucks, Buses)
- Non-vehicles (Pedestrians, Bicyclists, Motorcycles)

Most Harmful Event:
- Non-collision
- Collision with Fixed or Moving Objects
- Collision with Another Motor Vehicle

Distance to Object Struck:
- In Road
- Off Road

The actual coding used may be discerned from the program listings in Appendix J. As discussed in Section 4.3.2, the accident types were reduced to two categories for the current analysis. These were accidents involving passenger cars as case vehicles (ACCTYP = 1,2,4,7,8,9,17,20 and 22) and all other type involvements.

The accident types found in a 10,000 vehicle sample file are shown in Table 4-3.

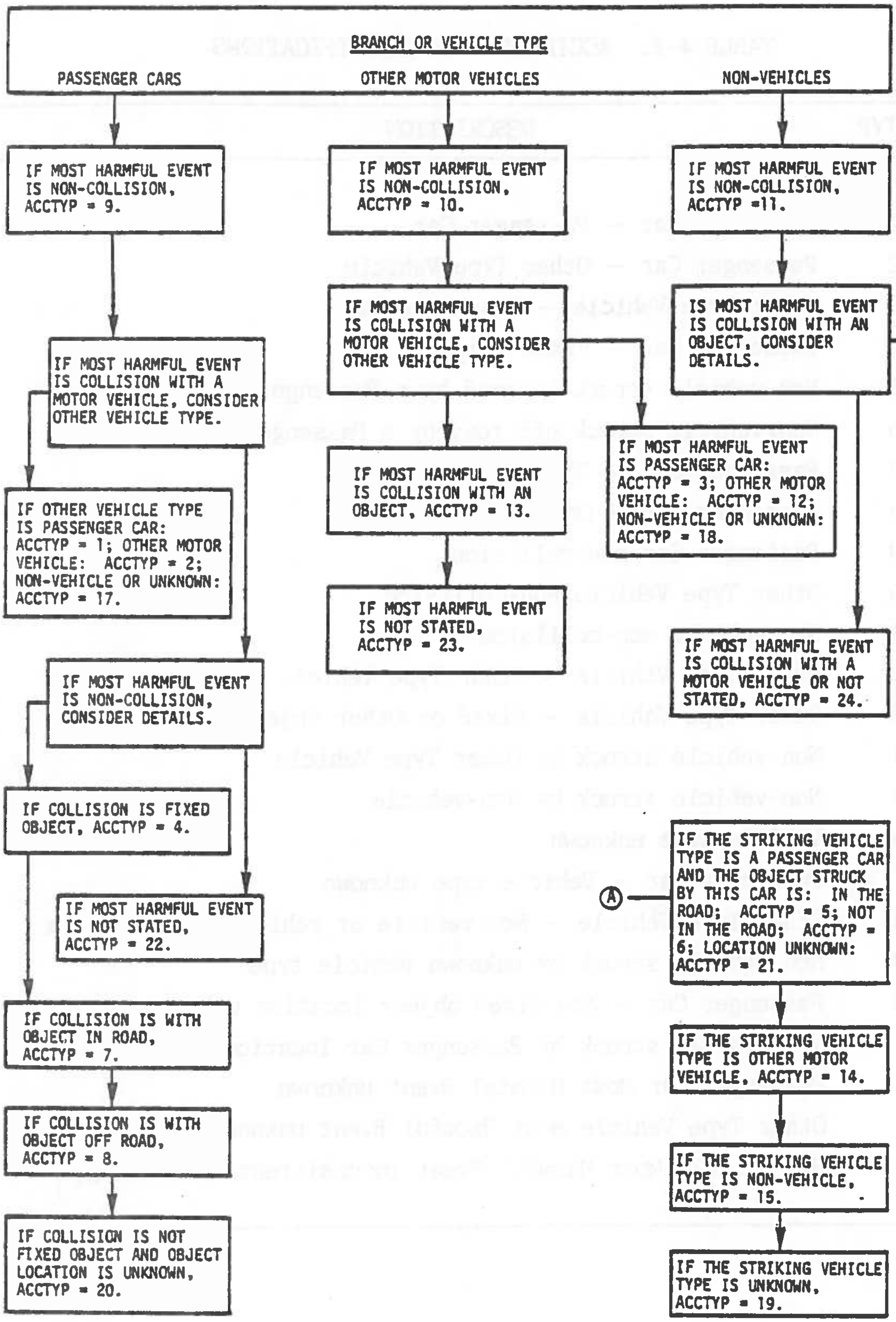


FIGURE 4-3. OVERVIEW FLOWCHART OF SUBROUTINE CLASS

TABLE 4-2. ACCIDENT TYPE CLASSIFICATIONS

ACCTYP	DESCRIPTION
1	Passenger Car - Passenger Car
2	Passenger Car - Other Type Vehicle
3	Other Type Vehicle - Passenger Car
4	Passenger Car - Fixed Object
5	Non-vehicle struck in road by a Passenger Car
6	Non-vehicle struck off road by a Passenger Car
7	Passenger Car - Object in Road
8	Passenger Car - Object off Road
9	Passenger Car non-collision
10	Other Type Vehicle non-collision
11	Non-vehicle non-collision
12	Other Type Vehicle - Other Type Vehicle
13	Other Type Vehicle - Fixed or Other Object
14	Non-vehicle struck by Other Type Vehicle
15	Non-vehicle struck by Non-vehicle
16	Vehicle type unknown
17	Passenger Car - Vehicle type unknown
18	Other Type Vehicle - Non-vehicle or vehicle type unknown
19	Non-vehicle struck by unknown vehicle type
20	Passenger Car - Non-fixed object location unknown
21	Non-vehicle struck by Passenger Car location unknown
22	Passenger Car Most Harmful Event unknown
23	Other Type Vehicle Most Harmful Event unknown
24	Non-vehicle Most Harmful Event inconsistent or unknown.

TABLE 4-3. FREQUENCY OF OCCURENCE OF INVOLVEMENTS BY ACCIDENT TYPE

ACCTYP	NUMBER
1	5169
2	1012
3	1032
4	990
5	7
6	3
7	199
8	127
9	313
10	94
11	12
12	261
13	263
14	3
15	0
16	70
17	53
18	9
19	7
20	322
21	13
22	26
23	17
24	6

4.3.4 Subroutine MODE

Accident selection and classification occur in the subroutine MODE. This subroutine evaluates each case (by case vehicle) in the North Carolina File and assigns values to variables which are to be used in later operations. KSPTYP, CONFIG, MU, XLENG2 and X20 are the variables assigned in MODE; they are introduced below.

KSPTYP denotes "KRAESP Type," referring to the KRAESP Program. The KRAESP Model functions by determining the consequences of various accidents (or, more precisely, groups of accidents). KSPTYP (which is sometimes referred to as "mode") is an input to the KRAESP Program and describes the case vehicle's configuration or geometry relative to the object it impacts. It also tells whether that object is a fixed object or another vehicle. The meanings of each of the eight possible values of KSPTYP are as follows:

KSPTYP=1	The front of Vehicle 1 (the case vehicle) impacts a fixed object ("Fixed-Object Front").
KSPTYP=2	Vehicle 1's side impacts a fixed object ("Fixed-Object Side").
KSPTYP=3	Vehicle 1 suffers a "non-collision" (typically a rollover), as opposed to an actual impact ("Rollover").
KSPTYP=4	Vehicle 1's front impacts another vehicle ("Vehicle-to-Vehicle Front").
KSPTYP=5	Vehicle 1's side impacts another vehicle ("Vehicle-to-Vehicle Side").
KSPTYP=6	Vehicle 1's rear impacts another vehicle ("Vehicle-to-Vehicle Rear").
KSPTYP=7	Vehicle 1 strikes a pedestrian, bicyclist, or motorcyclist.

KSPTYP=8 Insufficient information exists in the data file for the KRAESP Program to accurately predict the accident's consequences.

Accidents are broken down in this manner for several reasons. First, it is important to know whether the case vehicle is hit in the front, side or rear. The KRAESP Program uses Delta-V (computed from Vrel) to calculate accident costs; for a given Delta-V, these costs are a strong function of the direction of impact. By their nature, automobiles have more crush space in their front and rear than in their sides, and safety design is directed more toward frontal impacts, which occur most frequently. Second, it is helpful to discriminate between fixed objects and vehicles, due to the differences in their mass distributions. Third, it is useful to separate accidents in which the case vehicle strikes a pedestrian, bicyclist or motorcyclist (KSPTYP=7). These cases are unique in that a person outside of the case vehicle bears the brunt of the accident's cost and relatively little property damage is involved.

Finally, KSPTYP=8 was established for "insufficient data" accidents. These are accidents whose accident record simply does not permit us to either calculate its societal costs in the KRAESP Program or determine the likely effects of radar braking systems. Thus, any accident which meets either of these two criteria will be assigned KSPTYP=8. The ultimate result of an accident being classified as KSPTYP=8 is that it is not considered further in any calculations. Some common reasons for exclusion are given below:

- Travel or impact velocities are missing.
- Vehicle 1 is parked. (If Vehicle 1 strikes Vehicle 2 and Vehicle 2 is parked, then injury/fatality costs are assigned only to Vehicle 1 and property damage costs are assigned as in any two-vehicle collision.)
- Inconsistent data are present. For example, if the "Most Harmful Event" is "Rear end, slow or stop" and both vehicles have the most damage in their fronts, then KSPTYP=8. (Note also that collisions involving three or more vehicles are not considered.)

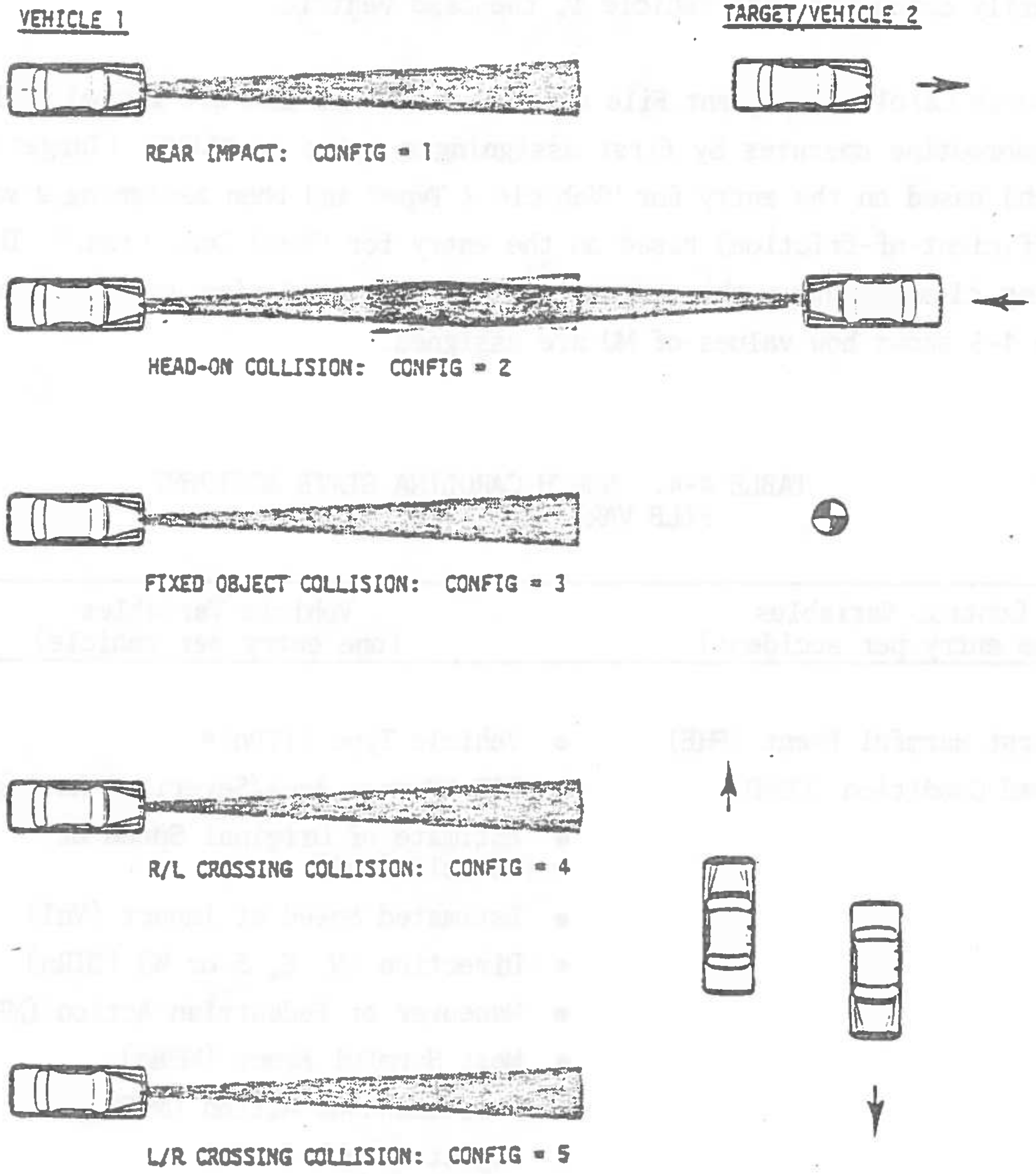
CONFIG represents "configuration" and assigns each accident to one of six categories. The purpose of the variable is to allow the RADAR Subroutine to make computations without an unneccessary degree of complexity. If desired, one could map each accident in the horizontal plane and formulate equations of motion for moving objects, locations for fixed objects, and boundaries for roads and parking lots, etc. Such an approach would be the most accurate, but it would also require a very lengthy analysis of a hardcopy data file and was not feasible in this effort. Instead, the basic accident kinematics were limited to the simplified configurations illustrated in Figure 4-4. In these configurations, Vehicle 1 is always a motor vehicle – the case vehicle – and Vehicle 2 may be any motor vehicle, pedestrian, bicyclist, or fixed object. Thus, it is perhaps more appropriate to simply refer to Vehicle 2 as the "target"; these two terms are used interchangeably in this text.

CONFIG=0 is assigned to any accident in which the presence of a radar braking system in the case vehicle would not have affected the outcome. In general, any vehicle that does not run into something will have CONFIG=0. Also, if the "Miscellaneous Action" entry indicates that the driver was maneuvering to avoid something or lost control of his vehicle (skidded out of control), then CONFIG=0.

Other grounds for assuming that radar will have no effect will be discussed later in this section. CONFIG=0 for all KSPTYP=8.

CONFIG=1, CONFIG=2 and CONFIG=3 are assigned to what we term "collinear accidents." In these, all motion is assumed to occur in a single dimension. Similiarly, CONFIG=4 and CONFIG=5 are assigned to "crossing accidents." In these, Vehicles 1 and 2 travel in perpendicular directions. All vehicles are assumed to be radar-equipped. However, the presence of radar in Vehicle 2 can only affect the accident's outcome in head-on accidents (CONFIG=2). In crossing accidents, Vehicle 1 always strikes Vehicle 2 in the side; hence, Vehicle 2 radar does not have an effect.

It is important to remember that the file being processed is a case vehicle file, which means that the same accident is often processed twice by MODE. Suppose, for instance, that a case is encountered in which Vehicle 1 strikes Vehicle 2 in the rear. MODE would typically assign KSPTYP=4 (Vehicle-to-Vehicle Front) and CONFIG=1, according to the conventions just specified. There would also be another case (either immediately preceeding or following) describing the same



(NOTE: CONFIG=0 WHEN RADAR BRAKES ARE NOT EXPECTED TO AFFECT THE ACCIDENT'S OUTCOME.)

FIGURE 4-4. FIVE BASIC CONFIGURATIONS IN RECONSTRUCTED ACCIDENTS accident, but in which Vehicle 1 is struck in the rear by Vehicle 2. For that case, MODE would assign KSPTYP=6 (Vehicle-to-Vehicle Rear) and CONFIG=0 since the presence of radar in Vehicle 1 would not have an effect. MODE is always primarily concerned with Vehicle 1, the case vehicle.

The North Carolina Accident File variables used in MODE are listed in Table 4-4. The subroutine operates by first assigning a value to XLENG2 (Target/Vehicle 2 length) based on the entry for "Vehicle 2 Type" and then assigning a value to MU (coefficient-of-friction) based on the entry for "Road Condition." The program listing clearly shows the assumptions made in assigning vehicle lengths, and Table 4-5 shows how values of MU are assigned.

TABLE 4-4. NORTH CAROLINA STATE ACCIDENT FILE VARIABLES USED IN "MODE"

Control Variables (one entry per accident)	Vehicle Variables (one entry per vehicle)
• First Harmful Event (FHE)	• Vehicle Type (TYPn)*
• Road Condition (COND)	• TAD (Damage Area/Severity) Ratings (TADn)
	• Estimate of Original Speed of Vehicle (VnT)
	• Estimated Speed at Impact (VnI)
	• Direction (N, E, S or W) (DIRn)
	• Maneuver or Pedestrian Action (MPAn)
	• Most Harmful Event (MHEn)
	• Miscellaneous Action (MISCn)
	• Object Struck (OBJn)
	• Struck Object Distance to Roadway (DISn)

* "n" may be 1 or 2.

TABLE 4-5. ASSUMPTIONS USED IN DETERMINING COEFFICIENT-OF-FRICTION

Entry	Surface Condition	Coefficient-of-Friction (MU)
0	Not Stated	Case not considered
1	Dry	0.6
2	Wet	0.4
3	Muddy	0.4
4	Snowy	0.3
5	Icy	0.2
6	Other	Case not considered

MODE then branches according to the Vehicle 1 entry for "Most Harmful Event" (variable MHE1). This coding probably tells more about the nature or configuration of the impact than any other variable. The remainder of this section will describe in some detail what happens for each of the 24 permissible entries for "Most Harmful Event" (Vehicle 1).

MHE1=0, "Not Stated." For this case, KSPTYP=8 (insufficient data).

MHE1=1, 2 or 3, "Ran Off Road." It is very common for a vehicle to run off the road ("First Harmful Event") and then overturn or strike something ("Most Harmful Event"). However, the act of running off the road is itself not very harmful and, when it is the most harmful thing that happens, we simply assign KSPTYP=8.

MHE1=4, "Non-Collision in Road - Overturn." For this case, KSPTYP=3 (Non-Collision) and CONFIG=0. These are typically cases in which a vehicle skids out of control and overturns. In such instances, it is doubtful that radar braking would be beneficial, but the presence of antiskid brakes could help the driver to retain control of his vehicle. Unfortunately, the ability of antiskid brakes to do this can only be assessed in a hardcopy analysis and is not considered here.

MHE1=5, "Other in Road." KSPTYP=8, due to insufficient data.

MHE1=6, "Collision of Motor Vehicle With Pedestrian." For these cases KSPTYP=7 and CONFIG are assigned primarily on the basis of "Maneuver or Pedestrian Action" (MPA2) for the target. If this entry is "Crossing at intersection," "Crossing not at intersection," "Coming from behind parked vehicle," "Playing in road" or "Getting on or off school bus," then CONFIG=4 (R/L Crossing). If MPA2 is "Walking with traffic," then CONFIG=1 (Rear Impact). If MPA2 is "walking against traffic," then CONFIG=2 (Head-on Impact). If MPA2 is "Getting on or off vehicle," "Standing in road" or "Working in road" then CONFIG=3 (Fixed-Object). Finally, if MPA2 is "Lying in road," "Other in road" or "Not in road," then we assume that the radar would not have seen the pedestrian and assign CONFIG=0. Moving pedestrians are assumed to travel at 3 mph (5 km/h).

MHE1=7, "Collision of Motor Vehicle With Parked Vehicle." In general, KSPTYP=1 (Fixed-Object Front) and CONFIG=3 (Fixed-Object) are assigned. If the most severe damage (from variable TAD1) on Vehicle 1 is somewhere other than on its front, then we assume that it must have skidded out of control and assign KSPTYP=2 (Fixed-Object Side) and CONFIG=0. When the case vehicle is the parked vehicle, we assign KSPTYP=8 and do not consider the case further.

MHE1=8, "Collision of Motor Vehicle With Train." Records for these accidents do not contain sufficient information to warrant examination — KSPTYP=8.

MHE1=9, "Collision of Motor Vehicle with Bicycle", and MHE1=10, "Collision of Motor Vehicle with Moped." KSPTYP=7, while CONFIG is assigned by comparing the directions of travel for Vehicle 1 and Vehicle 2 (the bicycle). For example, if DIR1=N and DIR2=S, then CONFIG=2 (Head-On Collision). In cases where either direction is missing, MODE simply uses the same configuration that was used in the last bicycle accident. If not given, the bicycle's travel and impact velocities are assumed to be 10 mph (16 km/h).

MHE1=11, "Collision of Motor Vehicle with Animal." Records for these accidents do not contain sufficient information to warrant examination — KSPTYP=8.

MHE1=12, "Collision of Motor Vehicle with Fixed Object." For these cases, MODE uses the "Object Struck" (OBJ1) entry to further distinguish the type of accident. If the entry is "Parked vehicle," "Bicycle or Moped," "Pedestrian" or "Animal," then the case is treated in the manner described above for each of these categories. If the entry is "Not stated," "None" or "Other object," then KSPTYP=8 is assigned due to insufficient information. Because the KRAESP Program was developed to analyze impacts with massive, non-yielding objects that would impart a sudden significant velocity change on an impacting vehicle, cases in which the struck objects clearly did not fit this description were also discarded. These struck objects included "Traffic island curb or median," "Catch basin or culvert on shoulder," "Catch basin or culvert in median," "Ditch bank," "Mailbox," "Fence or fence post," "Construction barrier" and "Crash cushion."

For all other objects (such as trees, guardrails, poles and barriers), either KSPTYP=1 or KSPTYP=2 was assigned, depending on where the impacting vehicle was damaged. If KSPTYP=1 and the object was no more than 10 feet (3 m) from the edge of the roadway (as determined by "Distance from Road," DIS1), then radar-braking is assumed to be likely and CONFIG=3 (Fixed-Object). Otherwise, CONFIG=0.

MHE1=13, "Collision of Motor Vehicle with Other Object." Records for these cases do not contain sufficient information to warrant further examination — KSPTYP=8.

"Collision of Motor Vehicle with Another Motor Vehicle": MHE14, "Rear end, slow or stop" and MHE1=15, "Rear end, turn." These collisions are generally conventional rear impacts, where much of the potential benefits of radar-braking systems are theorized to lie. For these accidents, MODE evaluates the vehicle damage areas and impact velocities to determine which is the striking and which is the struck vehicle. Usually, the striking vehicle is assigned KSPTYP=4 (Vehicle-to-Vehicle Front) and CONFIG=1 (Rear Impact), and the struck vehicle is assigned KSPTYP=6 (Vehicle-to-Vehicle Rear) and CONFIG=0.

"Collision of Motor Vehicle with Another Motor Vehicle": MHE16, "Left turn, same roadway"; MHE17, "Left turn different roadways"; MHE18, "Right turn, same roadway"; and MHE19, "Right turn, different roadways." These categories represent accidents which occur while one or both vehicles is in the process of turning. In general, KSPTYP=4, 5, 6 or 8 is assigned, according to Vehicle 1's damage. MODE also assigns CONFIG=0, which assumes that radar braking would have no value. This assumption is made primarily due to insufficient information about vehicle trajectories in the accident record, and will tend to overlook some potentially beneficial cases. In actuality, however, we do not expect radar braking to play a significant role here for these reasons:

- Most radar systems are either temporarily disabled or else range-limited while a vehicle is turning.
- The kinematics of these accidents are such that Vehicle 2 will rarely stay in Vehicle 1's radar field-of-view for more than a short period of time.
- Turning vehicles travel at lower-than-average speeds, so we would expect the severity of accidents involving them to generally be lower than average.

<u>MHE1=20, "Collision of Motor Vehicle with Another Motor Vehicle: Head On."</u> Here, KSPTYP=4 (Vehicle-to-Vehicle Front) and CONFIG=2 (Head-On Impact) are assigned, unless inconsistent or insufficient data are present.

<u>MHE1=21, "Sideswipe."</u> By its nature, a sideswipe is not a particularly harmful event, although it may often cause other, more damaging, occurrences. Because of issues associated with quantifying crash severity under this condition, we simply assign KSPTYP-8.

<u>MHE1=22, "Collision of Motor Vehicle with Another Motor Vehicle: Angle."</u> These accidents are defined in the North Carolina Coding Manual as collisions ". . . most often resulting in the vehicles hitting at or near right angles, with the front of one vehicle striking the side of the other vehicle." They form the basis for the crossing configurations. Vehicle damage is evaluated to determine which was the striking vehicle, which was the struck vehicle, and whether the accident was CONFIG=4 (R/L Crossing) or CONFIG=5 (L/R Crossing). Vehicle damage ratings are also used to assign a value (in feet) to X20, which is defined as the distance from the center of Vehicle 2 to the centerline of Vehicle 1 when the two vehicles impact. X20 will indicate whether Vehicle 1 strikes the front, middle or rear side of Vehicle 2. If Vehicle 1 strikes Vehicle 2 further toward the

rear, then it means that Vehicle 1's radar would have seen Vehicle 2 for a longer period of time and, thus, would have had a better opportunity to prevent or mitigate the accident.

MHE1=23, "Collision of Motor Vehicle with Another Motor Vehicle: Backup." These are generally accidents in which Vehicle 1 backs into a parked vehicle. They are, therefore, not severe in nature and certainly cannot be avoided with radar brakes. (Nobody has yet, to our knowledge, proposed putting radar on the backs of cars.) KSPTYP=8 is assigned.

4.3.5 Subroutine BRAKE

Subroutine BRAKE reconstructs accidents according to one of the configurations shown in Figure 4-4. If N radar systems are being evaluated, BRAKE will calculate N+1 values of relative velocity (Vrel). One Vrel is for the null (no radar) case and represents the Vrel which occurred in the documented accident. The other Vrels represent the values which would be observed if the vehicles had been equipped with the radar systems under study. The difference between a predicted Vrel and the null Vrel provides a good measure of how well a radar system might have mitigated the accident. If a system causes the accident to be avoided entirely, then Vrel=0.

A simplified flowchart for the BRAKE subroutine is shown in Figure 4-5. The variables KSPTYP and CONFIG were specified in the preceding subsection. SYSTYP is a number which defines the radar system being evaluated and ISYS is the total number of radar systems. Other variables in the flowchart are defined below.

- t_o represents the beginning of a computational time interval. All times in BRAKE are specified such that t=0 when the collision occurs in the null case. Therefore, most events will occur at negative values of t and the collision itself will occur at t=0 or, if it is delayed, at positive t.
- t_f represents the end of a computational time interval.
- t_{1b} represents the time when Vehicle 1 (the case vehicle) begins braking. If the vehicle does not brake then t_{1b} = 10.

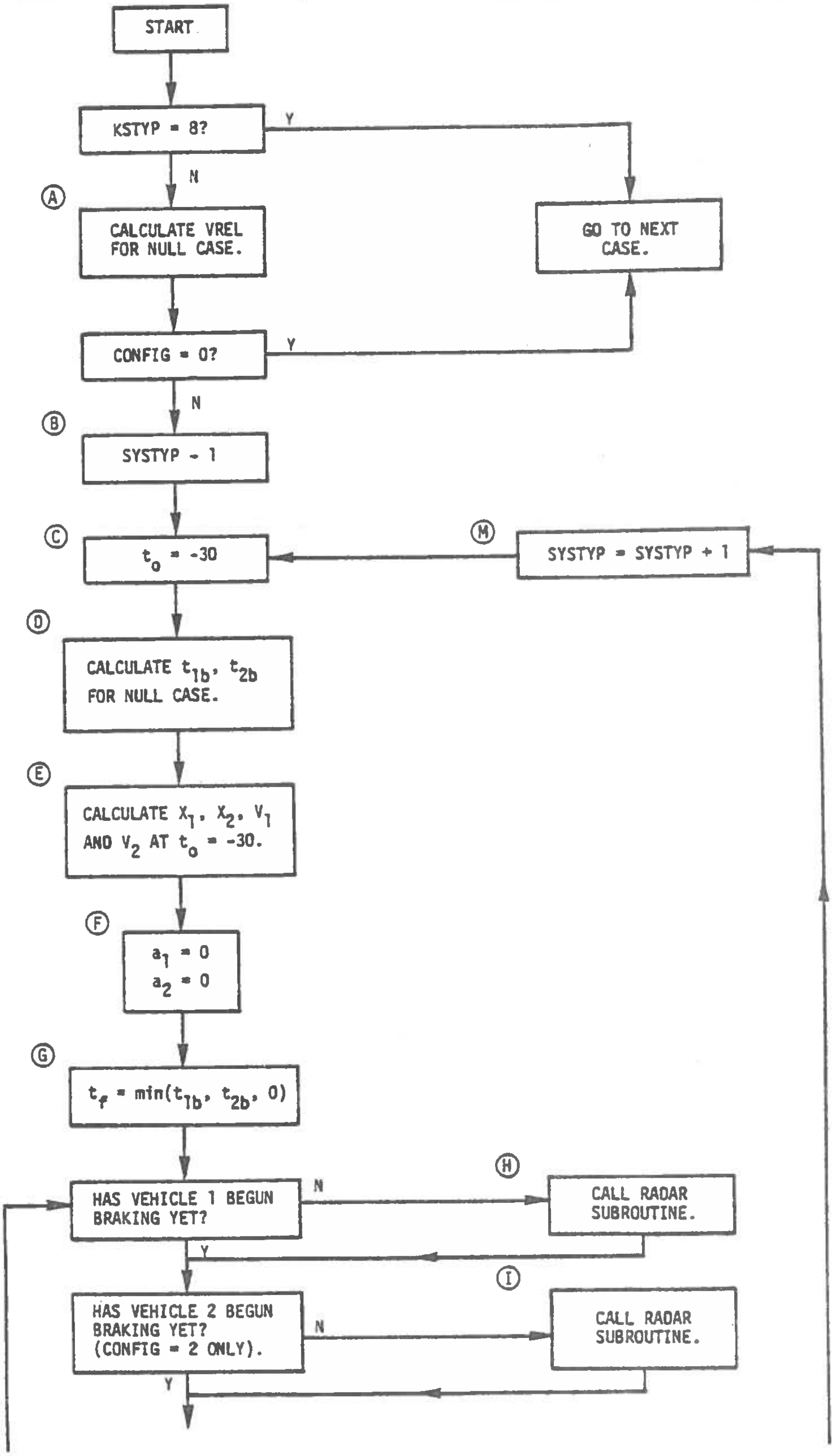


FIGURE 4-5. OVERVIEW FLOWCHART OF SUBROUTINE BRAKE

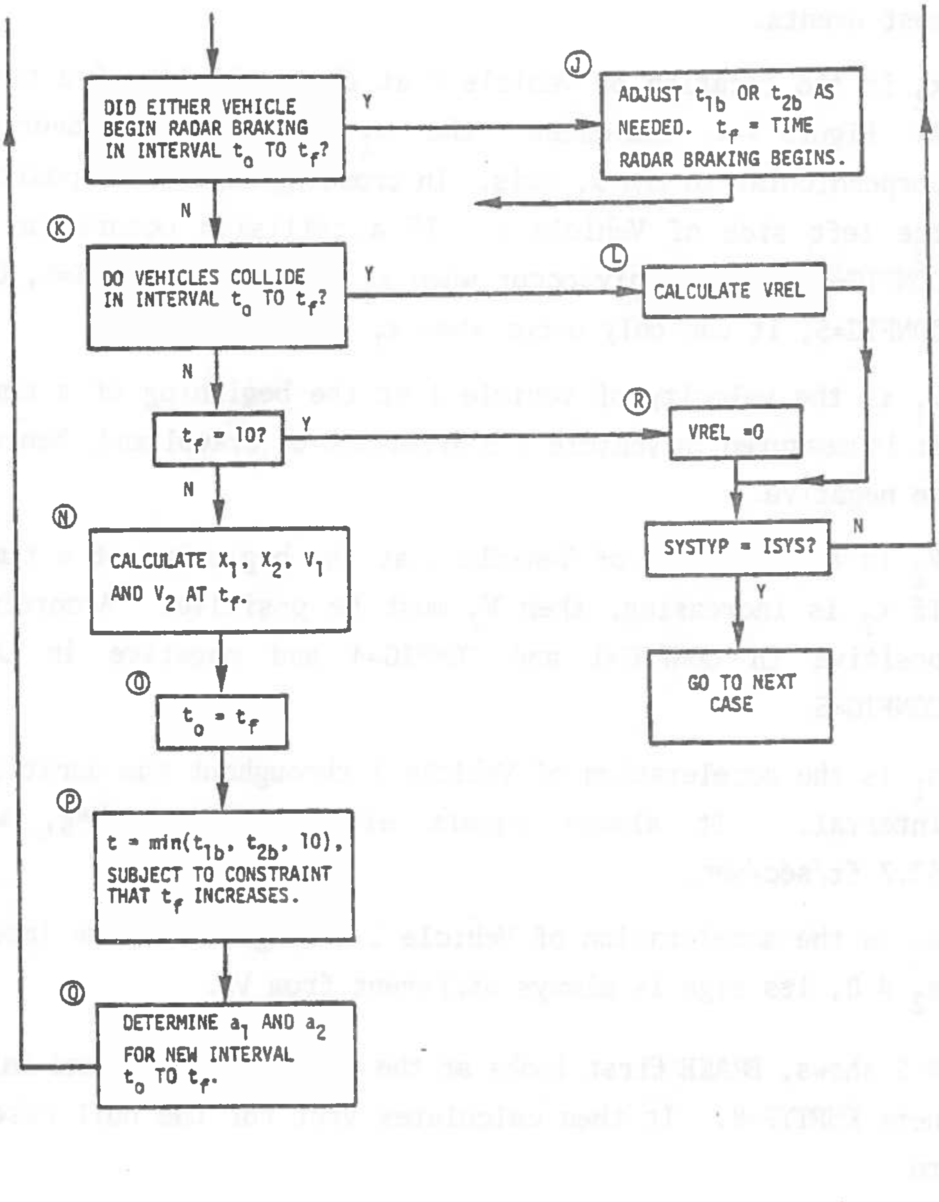


FIGURE 4-5. (Cont'd)

- t_{2b} represents the time when Vehicle 2 begins braking. If the vehicle does not brake then $t_{2b} = 10$.
- x_2 is the location of the front of Vehicle 1 at the beginning of a computational time interval. It is measured in feet and specified such that $x_1 = 0$ when impact occurs in the null case. Positive x_1 is in the direction of Vehicle 1's motion, which means that x_1 is negative for most events.
- x_2 is the location of Vehicle 2 at the beginning of a time interval. As Figure 4-4 indicates, the x_2 axis either overlays or is perpendicular to the x_1 axis. In crossing collisions positive x_2 is on the left side of Vehicle 1. If a collision occurs in CONFIG=1 or CONFIG=2, it can only occur when $x_1 = x_2$. In CONFIG=3, CONFIG=4 and CONFIG=5, it can only occur when $x_1 = 0$.
- V_1 is the velocity of Vehicle 1 at the beginning of a time interval. It is measured in Vehicle 1's direction of travel and, hence, can never be negative.
- V_2 is the velocity of Vehicle 2 at the beginning of a time interval. If x_2 is increasing, then V_2 must be positive. Accordingly, V_2 is positive in CONFIG=1 and CONFIG=4 and negative in CONFIG=2 and CONFIG=5.
- a_1 is the acceleration of Vehicle 1 throughout the duration of a time interval. It always equals either 0 or -MU*g, where g is 32.2 ft/sec/sec.
- a_2 is the acceleration of Vehicle 2 throughout a time interval. When $a_2 \neq 0$, its sign is always different from V_2.

As Figure 4-5 shows, BRAKE first looks at the variable KSPTYP and only continues in cases where KSPTYP=8. It then calculates Vrel for the null case (Block A), according to

For Fixed-Object Impact or Hit Parked Vehicle	Vrel = V1I
For Vehicle-to-Vehicle Impact where KSPTVP of second vehicle is not known	$Vrel = (V2I^2 + V2I^2)^{1/2}$

For Head-On Impact $Vrel = V1I + V2I$

For Side Impact $Vrel = (V1I^2 + V2I^2)^{1/2}$

For Rear-End Impact $Vrel = V1I - V2I$

All of the above for the unmodified Vrel. For the modified Vrel, the following formulas are used.

Fixed-Object Front $Vrel = 0.252/CFM + 0.363 * V1I$

Fixed-Object Side $Vrel = 0.038/CFM + 0.329 * V1I$

Rollover/Non-Collision $Vrel = 3./CFM$

Vehicle-to-Vehicle Front $Vrel = -7.508/CFM + 0.684 + V2I + 0.534 * V1I$

Vehicle-to-Vehicle Side $Vrel = -2.088/CFM + 0.614 + V2I + 0.179 * V1I$

Vehicle-to-Vehicle Rear $Vrel = -3.798/CFM + 0.862 = V2I - 0.851 * V1I$

Pedestrian $Vrel = V1I$

In the above calculation, V1I and V2I are the two vehicles' impact velocities, obtained from the accident record. (Note that these impact velocities are always positive, unlike the BRAKE vehicle velocities which were just defined.)

If CONFIG=0, BRAKE assumes that none of the radar systems will have any effect in the accident and does not go further. Vrel for each system simply equals Vrel for the null case. Otherwise, BRAKE starts to reconstruct the accident as it would have occurred with the first radar system (Block B).

Accidents are reconstructed through a series of discrete, continuous time intervals, each of which begins at time t_o and ends at time t_f. During any interval, the positions and velocities of both vehicles may change, but they always undergo constant acceleration. One interval ends and another begins when either vehicle changes its acceleration, either by applying its brakes or coming to a stop. The beginning of the first interval is arbitrarily set at t_o = -30 sec (Block C).

BRAKE initially assumes that both vehicles travel at a constant velocity (equal to the travel velocity specified in the accident record), apply their brakes, and then uniformly decelerate until they reach impact velocity and collide. When a vehicle's travel velocity equals its impact velocity, then braking is assumed not to occur. Using these assumptions, BRAKE calculates initial values of t_{1b} and t_{2b} (Block D), and computes the initial positions and velocities at the beginning of the first time interval (Block E). Both vehicle accelerations are set equal to zero (Block F). The first interval is set to end when one of the vehicles begins braking or, if neither brakes, to the time when the collision occurs, t=0 (Block G).

The subroutine then begins the process of evaluating each time interval. First, it calls the RADAR subroutine (twice in head-on collisions) to determine if either vehicle would have started braking sooner with radar brakes than it did in the actual accident (Blocks H and I). The RADAR subroutine may respond by specifying a new brake activation time (see Section 4.3.6). When this happens, the immediate effect is to shorten the time interval so that it ends when one of the vehicles begins braking (Block J). The deceleration which results from radar-applied braking will not be be seen until the next interval, however. In addition to applying the brakes earlier, radar braking will also be expected to increase the coefficient-of-friction somewhat over that attained by average drivers. Therefore, whenever a vehicle radar-brakes, its value of MU increases by 0.1.

After t_f has been firmly established, BRAKE determines if a collision occurs during the interval (Block K). If so, a new Vrel is calculated (Block L) and the program moves on to consider the next radar system (Block M). If a collision does not occur, the subroutine's next step is to set up the initial parameters for the next interval. This is done by calculating vehicle positions and velocities at the end of the current interval (Block N), using the equations shown below:

$$V_1\ (t_f) = V_1 + a_1\ (t_f - t_o)$$
$$V_2\ (t_f) = V_2 + a_2\ (t_f - t_o\ )$$
$$x_1\ (t_f) = x_1 + V_1\ (t_f - t_o) + \frac{1}{2}\ a_1\ (t_f - t_o)^2$$
$$x_2\ (t_f) = x_2 + V_2\ (t_f - t_o) + \frac{1}{2}\ a_2\ (t_f - t_o)^2$$

Then t_o is set equal to t_f, specifying the beginning of the next interval (Block O). The next interval's endpoint, t_f, is set equal to the time of the next acceleration change (Block P) and, finally, new vehicle acelerations are specified (Block Q).

BRAKE continues to loop through the intervals until either a collision occurs or $t_f = 10$. If no accident has occurred by that time, then Vrel = 0 is specified (Block R) and the algorithm moves on to process the same case using the next radar system.

4.3.6 Subroutine RADAR

Subroutine RADAR is a series of subprograms which determine the time, T, at which the radar will activate the case vehicle's brakes. If the case vehicle does not have its brakes activated during the interval specified by the calling program, then the routine returns a value of 11 for the variable T.

The operation of RADAR is detailed by the flowchart in Figure 4-6. The essential functional steps are the following:

1. If no radar is used (Radar System 1), return T=11 (no radar braking).
2. Convert all vehicle trajectory variables to new variables consistent with the conventions used in radar.
3. For side impacts (CONFIG = 4,5), determine when the crossing vehicle would enter the beam as determined by the beam halfwidth, THETA (Figure 4-7).

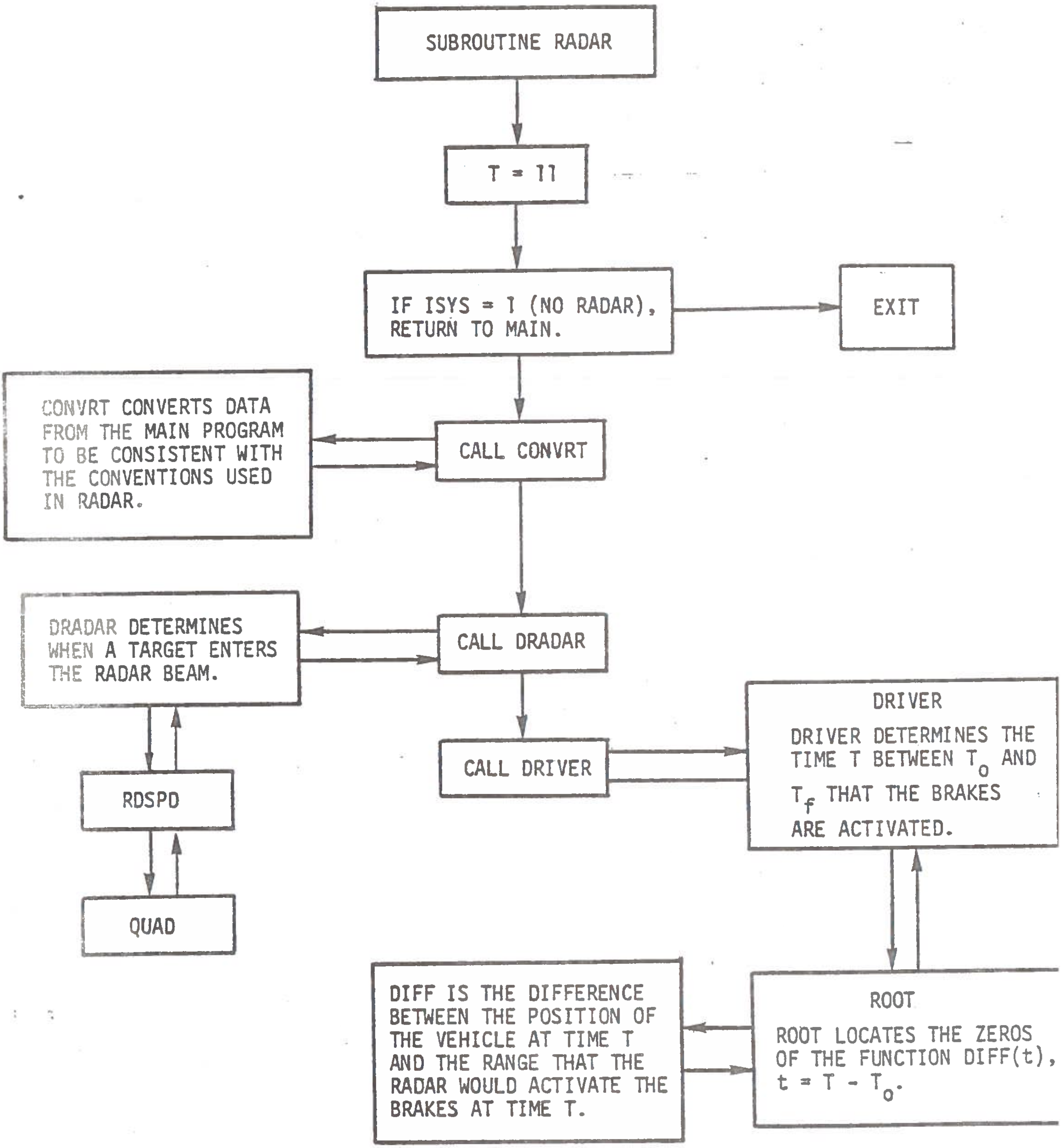
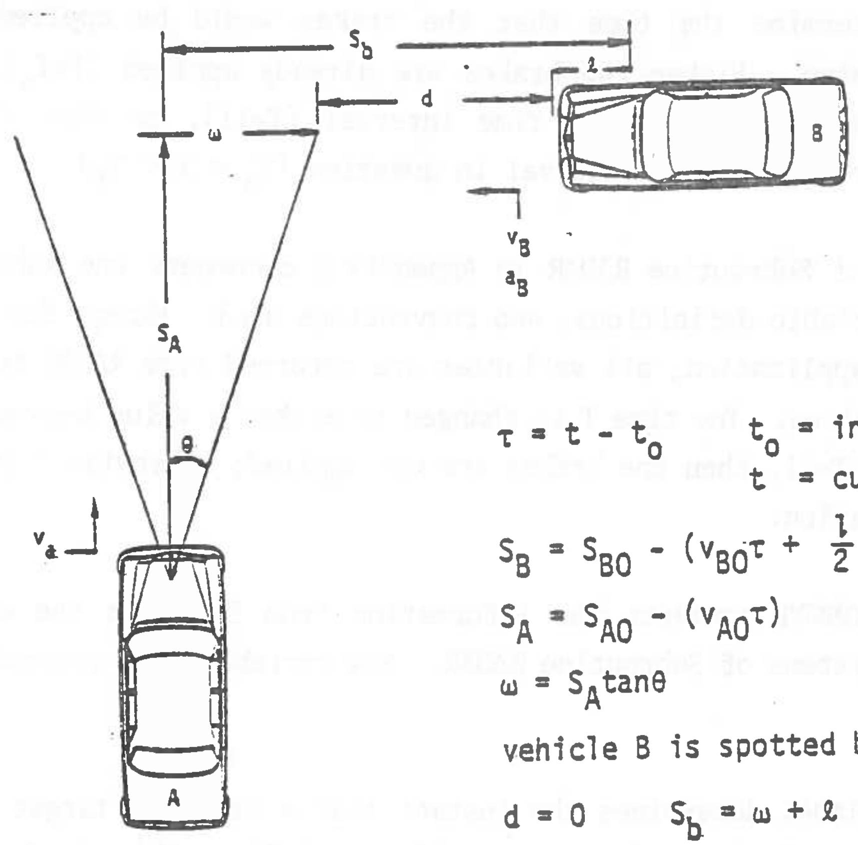


FIGURE 4-6. OVERVIEW FLOWCHART OF SUBROUTINE RADAR



$\tau = t - t_o$ $\quad t_o$ = initial time

$\quad t$ = current time

$$S_B = S_{BO} - (v_{BO}\tau + \frac{1}{2} a_B \tau^2)$$

$$S_A = S_{AO} - (v_{AO}\tau)$$

$$\omega = S_A \tan\theta$$

vehicle B is spotted by A when

$$d = 0 \quad S_b = \omega + \ell$$

$$(S_{AO} - v_{AO}\tau)\tan\theta + \ell = S_{BO} - v_{BO}\tau - \frac{1}{2} a_B \tau^2$$

$$\frac{1}{2} a_B \tau^2 + (v_{BO} - v_{AO}\tan\theta)\tau + (S_{AO}\tan\theta - S_{BO} + \ell) = 0$$

$$A\tau^2 + B\tau + C = 0$$

$$\left\{ \begin{array}{l} \tau_1 = -(B + \text{sign}(B)\sqrt{B^2 - 4AC}\,)/(2A) \\ \tau_2 = \dfrac{C}{\tau_1 A} \end{array} \right\} \text{ select the smallest positive root}$$

$$t = \tau + t_o$$

if $(t > t_f)$ Brakes are not applied in this interval

if $(t_f > t > t_o)$ $\quad t_o = t_f$

if $t < t_o$ $\quad t_o = t_o$

FIGURE 4-7. DESCRIPTION OF THE METHOD FOR CALCULATING ENTRY OF A CROSSING VEHICLE INTO THE RADAR BEAM

4. Determine the time that the brakes would be applied by the radar system. Either the brakes are already applied ($T=T_o$), they will be applied in a future time interval (T=11), or they will be applied during the time interval in question ($T_o < T < T_f$)

The listing of Subroutine RADAR in Appendix C documents the subroutine calling sequence, variable definitions, and conventions used. Except for T, the time of radar brake application, all variables are returned from RADAR to BRAKE exactly as they are given. The time T is changed to either a value between T_o and T_f or to T=11. If T=11, then the brakes are not applied; otherwise T is the moment of brake application.

Subprogram CONVRT converts the information from BRAKE to the conventions and coordinate systems of Subroutine RADAR. New variables are created to accomplish this.

Subprogram DRADAR determines the instant that a crossing target vehicle enters the periphery of the radar system (Figure 4-7). This is done by solving equations of motion for the radar beam and the target vehicle. The spread of the radar is defined by the angle THETA. DRADAR references two subroutines:

RDSPD	Sets up equations for moving target.
QUAD	Solves the equations of RDSPD.

If the target vehicle does not enter the detection zone until some time after T_o, the interval of investigation is narrowed so that the initial time becomes the time at which the target vehicle enters the radar's field of view.

Subprogram DRIVER determines the actual time of radar braking. If the distance to the target at the end of the time interval exceeds the radar brake activation range, then no braking occurs and T=11 is returned. If the distance to the target at the beginning of the interval is less than the radar activation range, then braking must have already begun and $T=T_o$ is returned. If $T_o \leq T \leq T_f$, then Subprogram ROOT is called to find the value of T. If T is earlier than a crossing vehicle actually enters the radar beam, then T is set equal to the time of entry into the beam.

Subprogram ROOT solves numerically for the time T at which the function DIFF becomes zero. DIFF (SYSTYP, TZERO, T) is the difference between the actual range to target and the activation range of the radar brake system at time T. (See Figure 4-8.)

Function DIFF contains the radar control law formulas which are used to determine the radar activation range as a function of vehicle velocities and time parameters. The functions used for the four radar systems are:

System 2: $R_B = 2\dot{R} + S$

System 3: $R_B = \dot{R}^2/2\mu g + \tau\dot{R} + S$

System 4: $R_B = V_1^2/2\mu g - V_2^2/2\mu g + \tau V_1 + S$

System 5: $R_B = V_1^2/2\mu g \pm V_2^2/2\mu g + \tau V_1 + S$ (+ if head-on)

where

R_B is the radar brake actuation range.

V_1 is the radar vehicle speed.

V_2 is the target vehicle speed.

μ, τ, and S are constants which may be set separately for each radar system.

g is the gravitational acceleration.

(All units are feet per second.)

The radar system performance functions are shown in Figures 4-9 through 4-16.

4.4 COMPUTATIONAL RESULTS AND BENEFITS CALCULATIONS

The Radar Brake Algorithm used in conjunction with the KRAESP Model is able to predict the number of injuries and fatalities to vehicle occupants, the number of non-occupant injuries and fatalities, and the property damage losses occurring

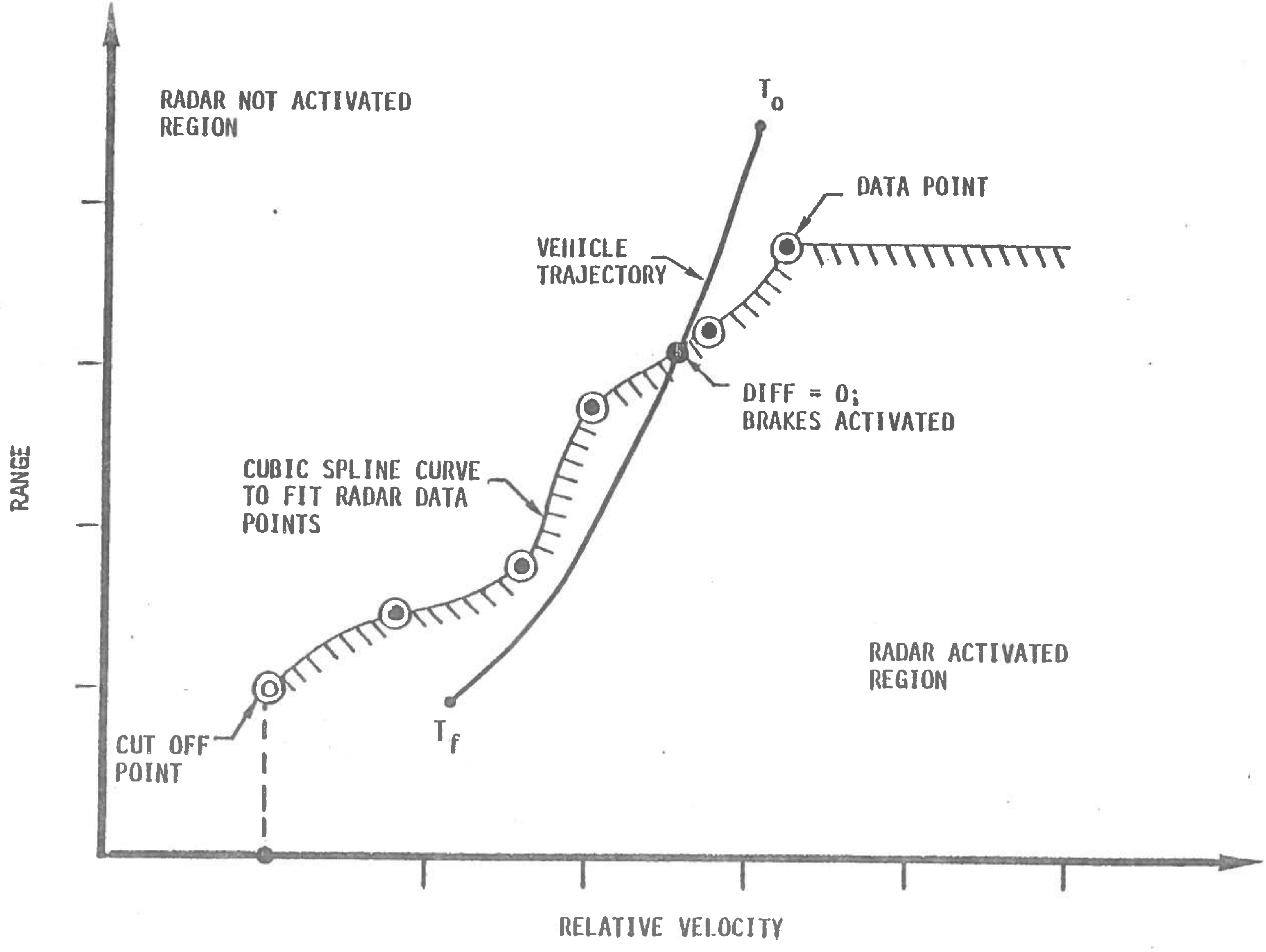


FIGURE 4-8. GEOMETRIC INTERPRETATION OF SUBPROGRAM DRIVER

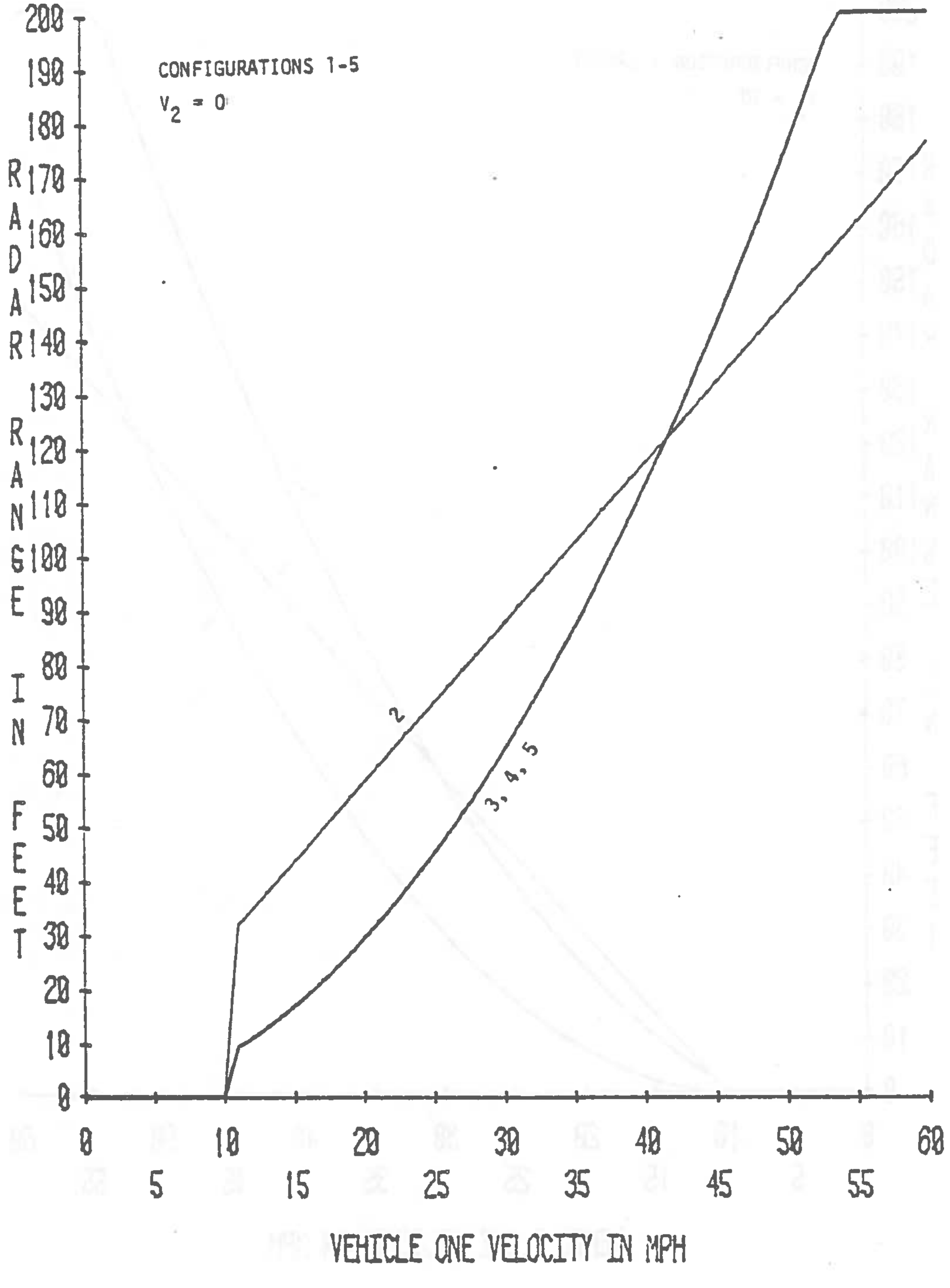


FIGURE 4-9. RADAR SYSTEM PERFORMANCE FUNCTIONS, CONFIGURATION 1-5

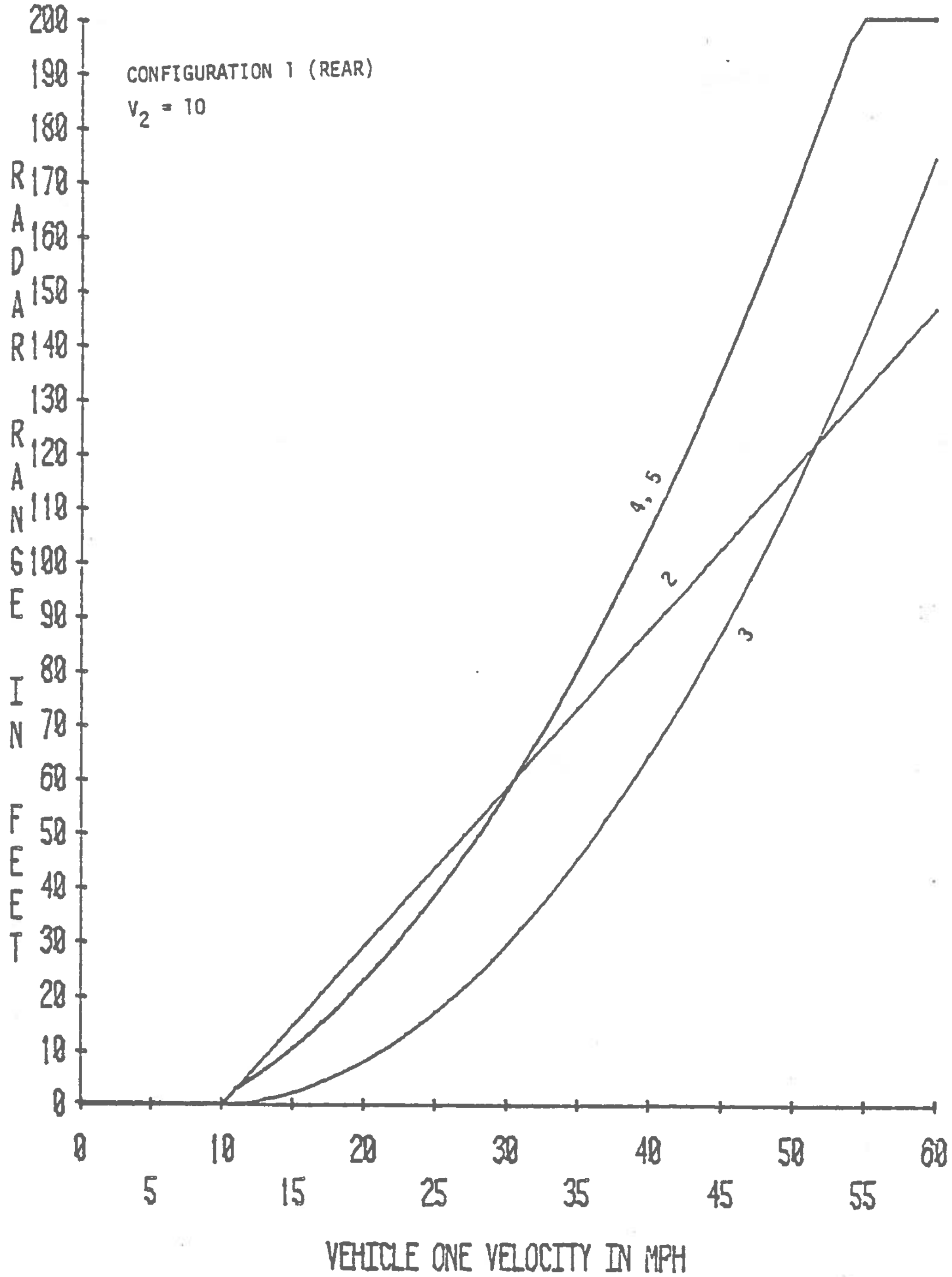


FIGURE 4-10. RADAR SYSTEM PERFORMANCE FUNCTION, CONFIGURATION 1 (REAR)

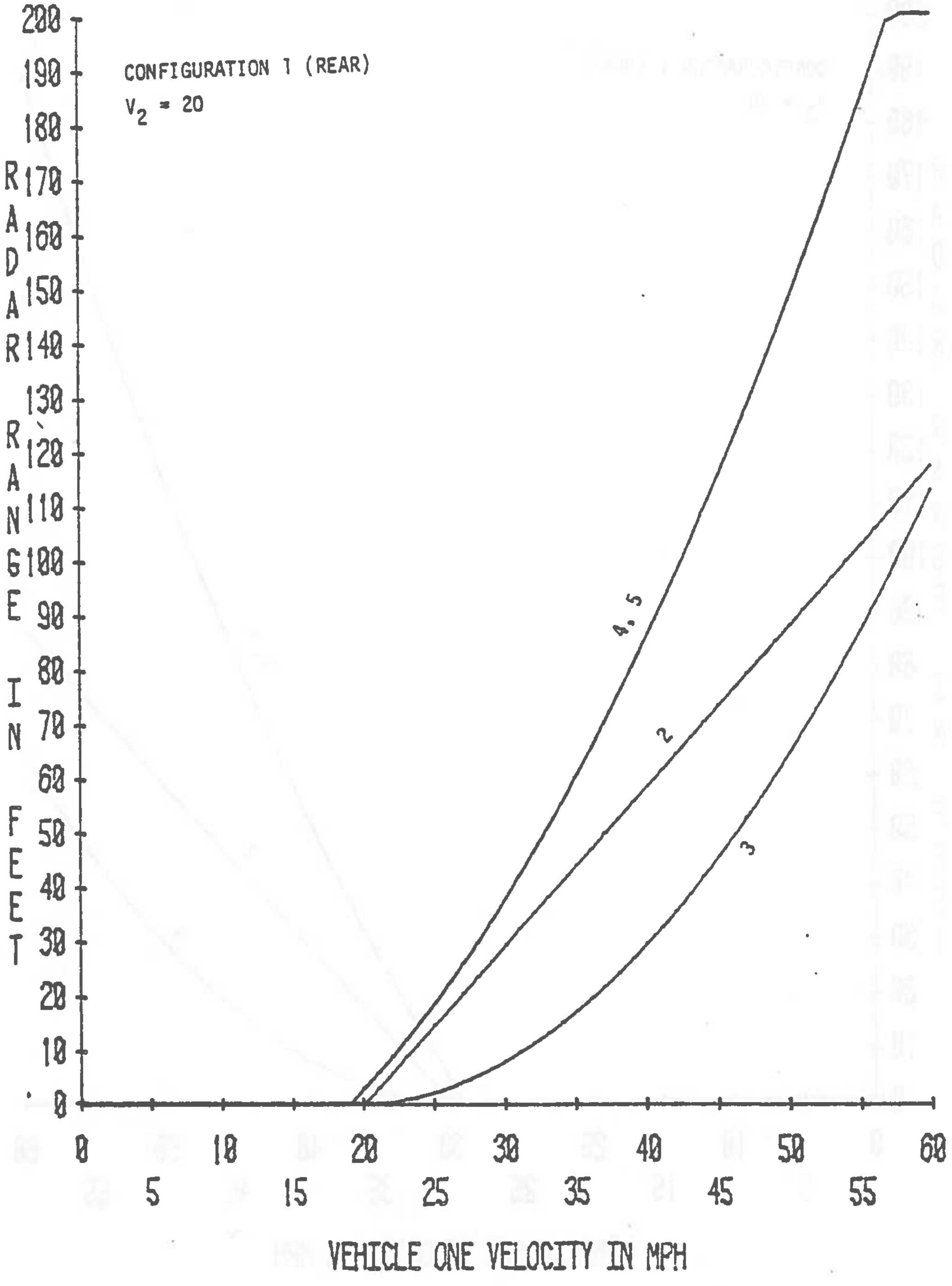


FIGURE 4-11. RADAR SYSTEM PERFORMANCE FUNCTION, CONFIGURATION 1 (REAR)

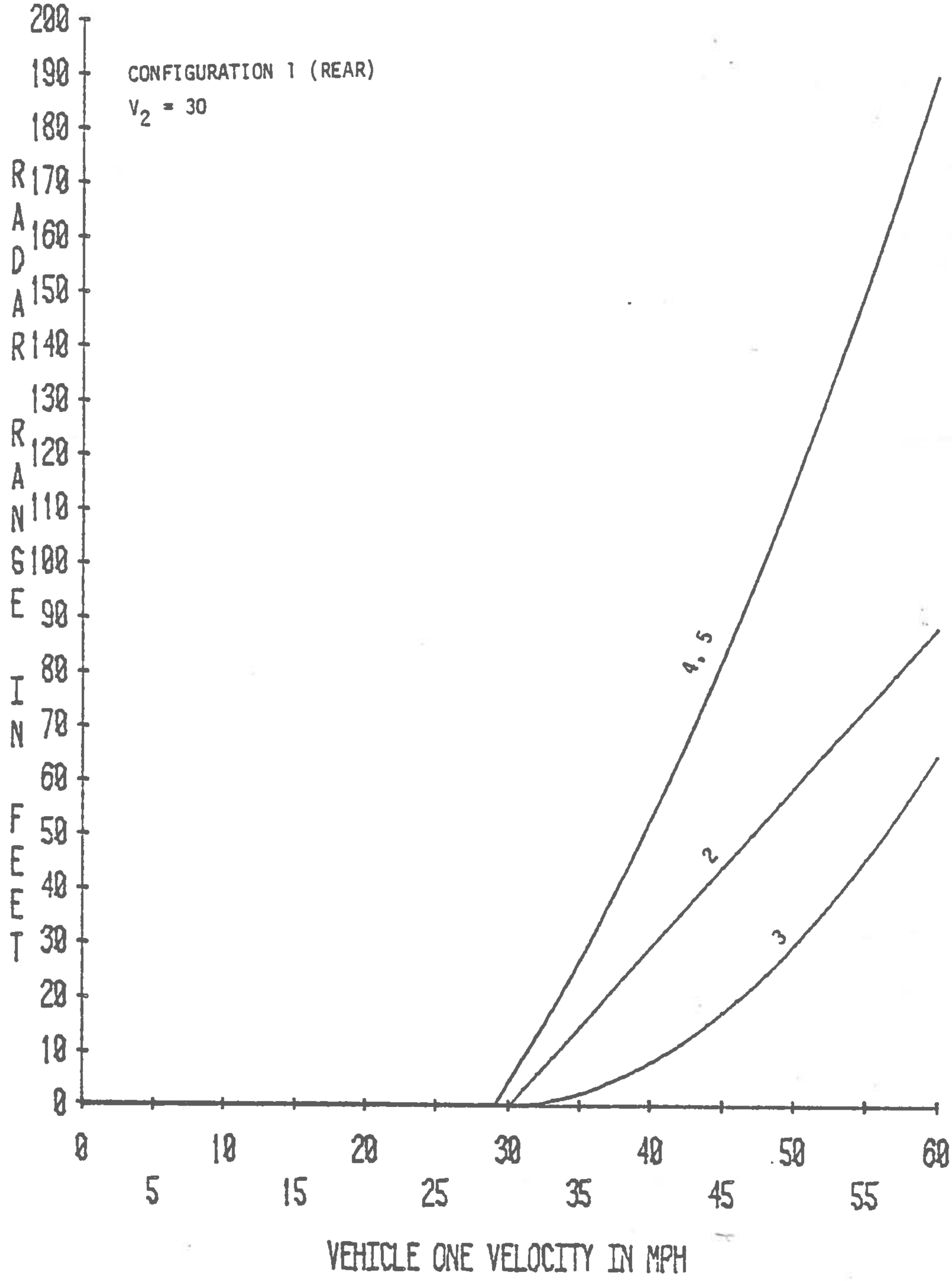


FIGURE 4-12. RADAR SYSTEM PERFORMANCE FUNCTION, CONFIGURATION 1 (REAR)

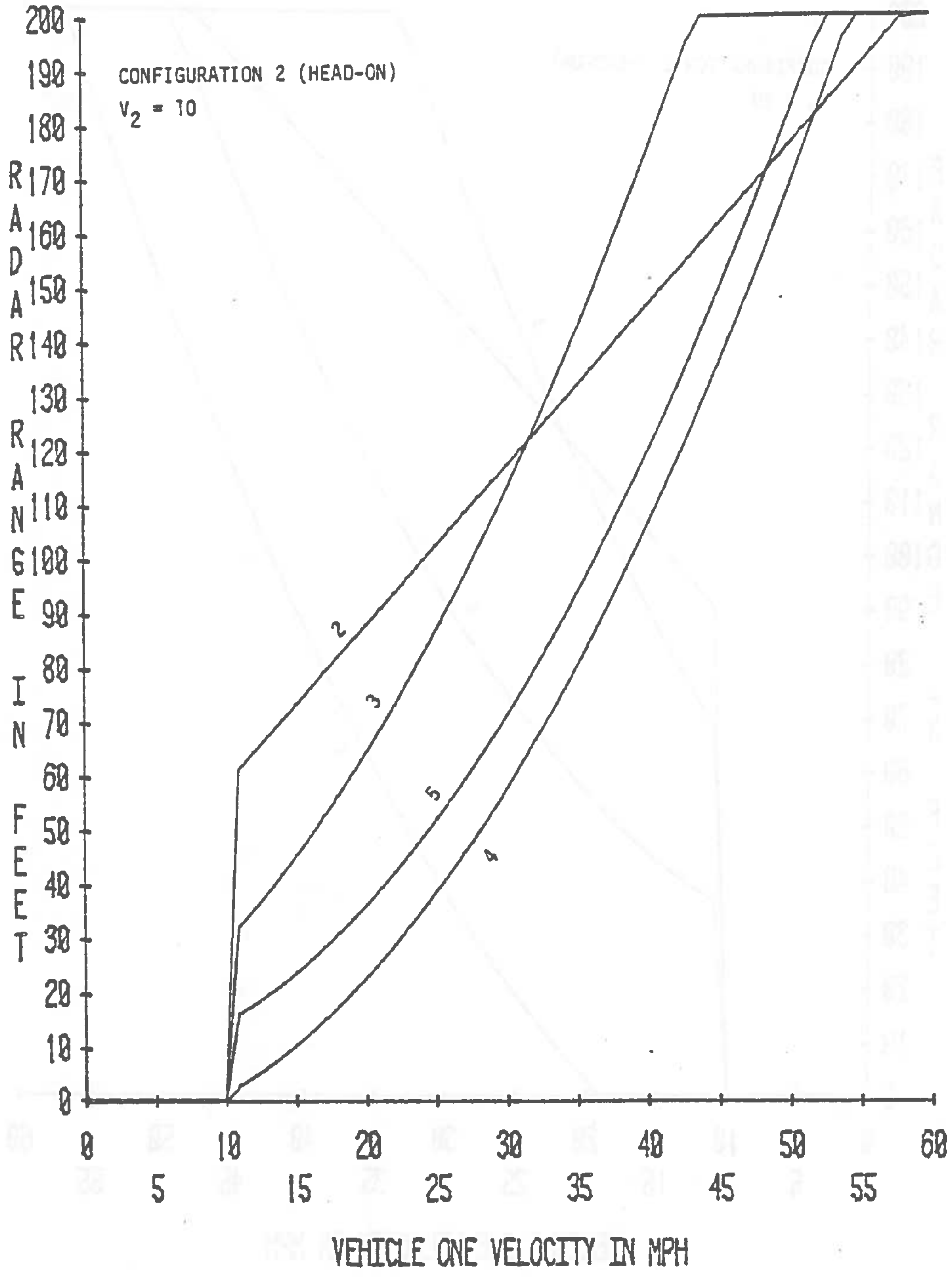


FIGURE 4-13. RADAR SYSTEM PERFORMANCE FUNCTION, CONFIGURATION 2 (HEAD-ON)

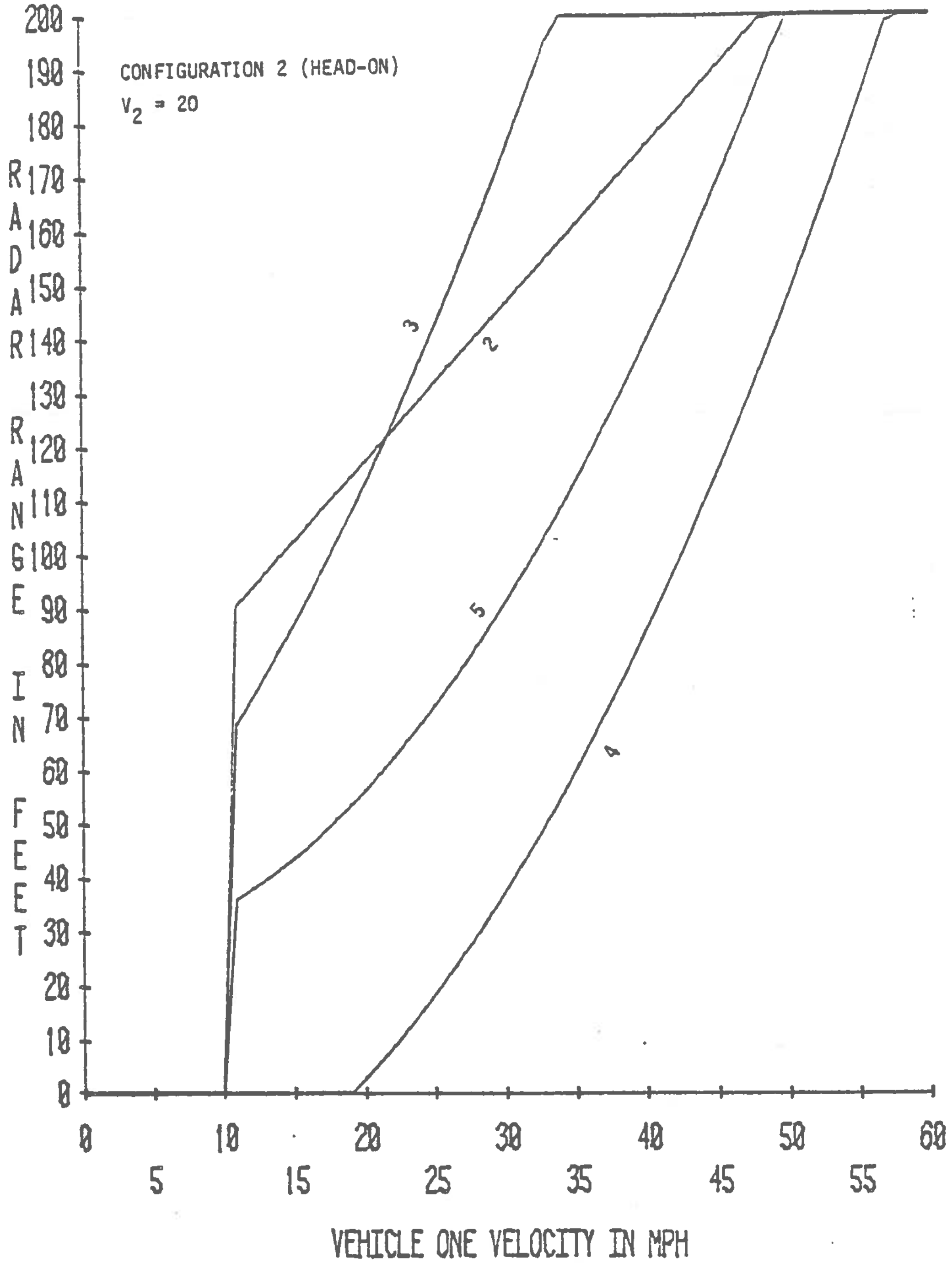


FIGURE 4-14. RADAR SYSTEM PERFORMANCE FUNCTION, CONFIGURATION 2 (HEAD-ON)

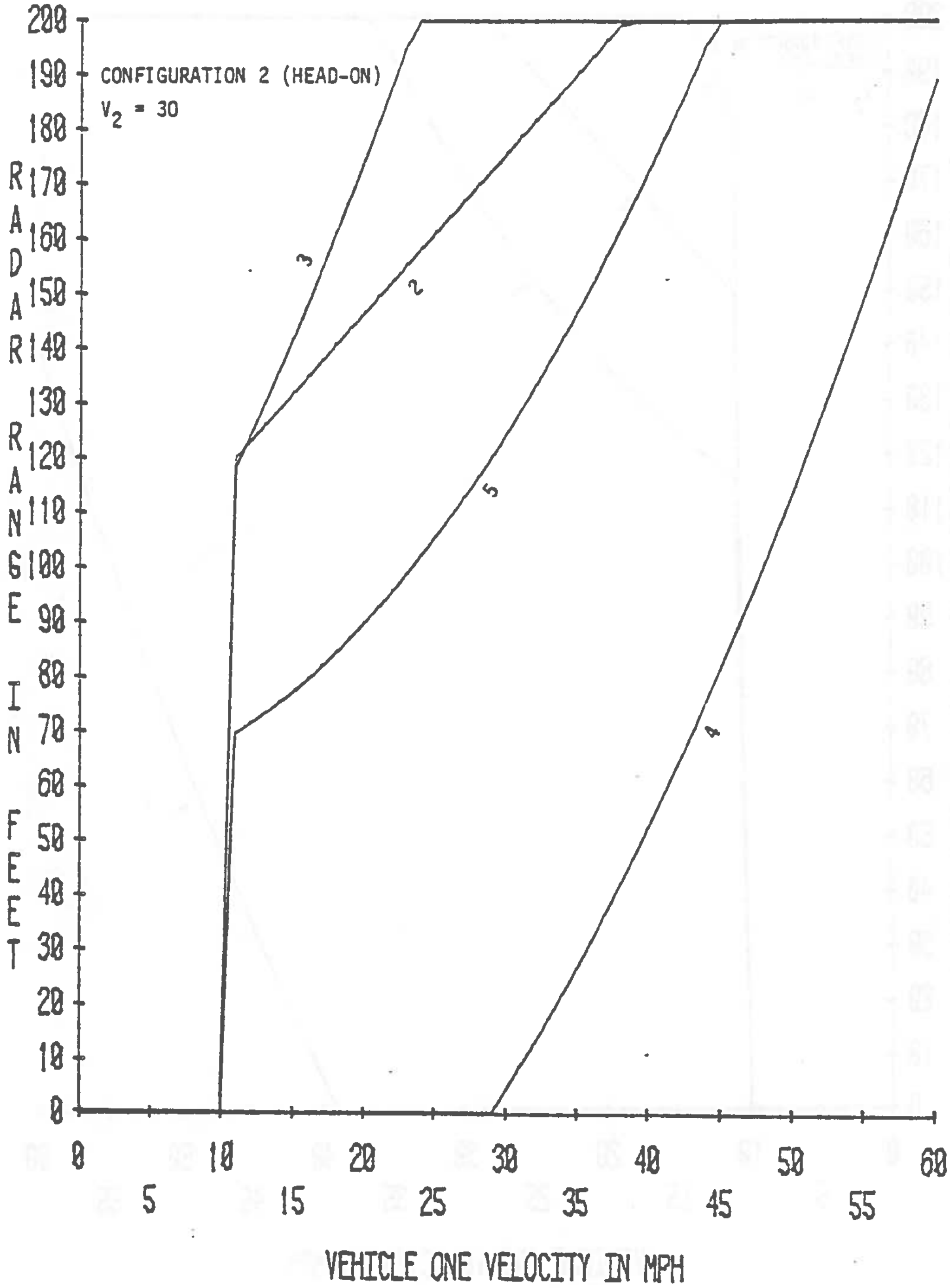


FIGURE 4-15. RADAR SYSTEM PERFORMANCE FUNCTION, CONFIGURATION 2 (HEAD-ON)

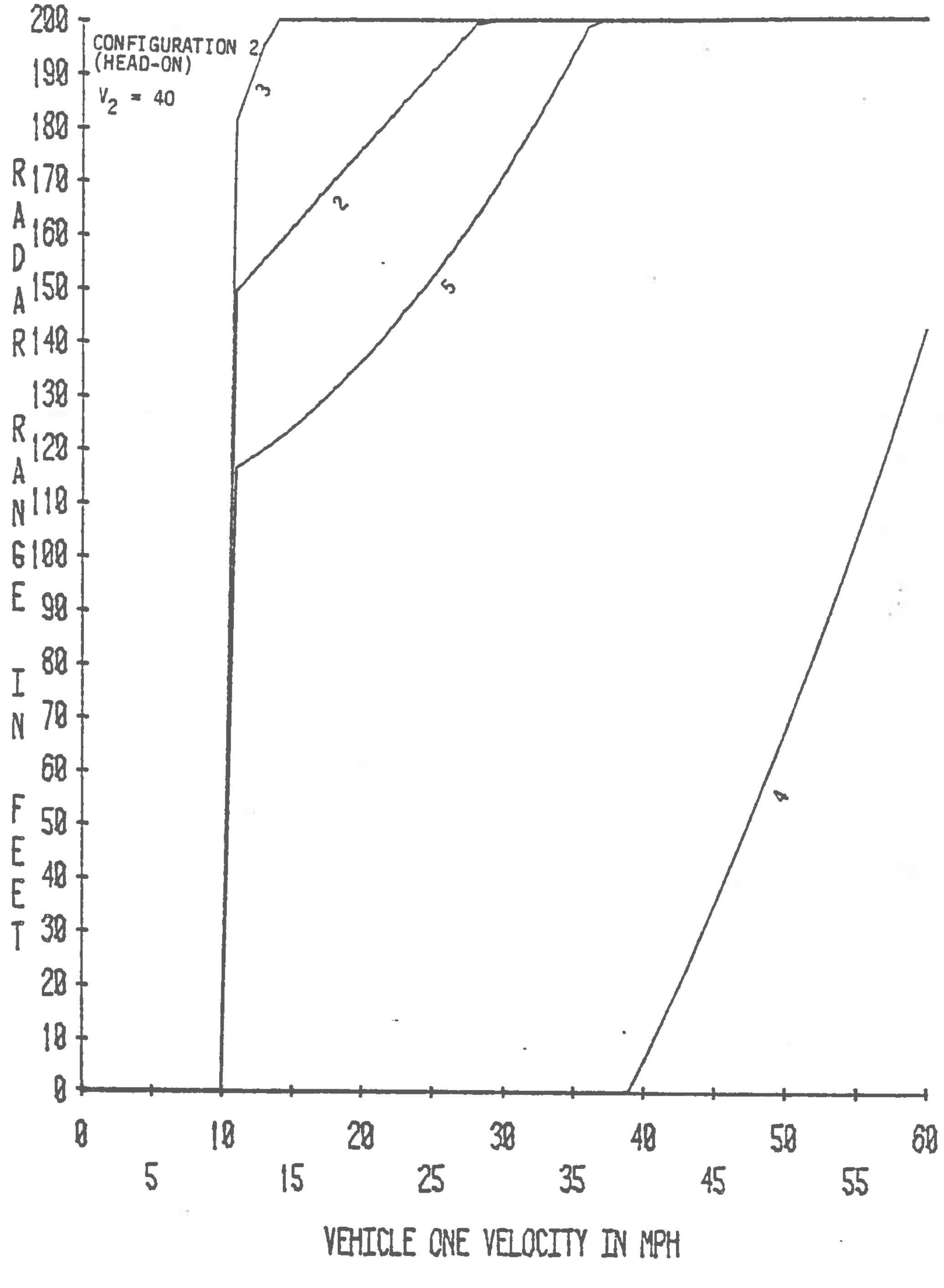


FIGURE 4-16. RADAR SYSTEM PERFORMANCE FUNCTION, CONFIGURATION 2 (HEAD-ON)

in the tabulated accidents. All of these quantities are predicted for each of the four radar systems and for the baseline system which represents the actual, no-radar, system. The vehicle occupant injuries and fatalities are predicted by the KRAESP Model from the probability distribution of Vrel within each of the several accident configurations. The non-motorist injuries and fatalities and property damage are predicted by the Radar Brake Algorithm itself from formulas relating injury and property damage directly to Vrel for each case.

Certain assumptions that are made in the KRAESP Model require that the Vrel probability distributions, which are computed directly from the vehicle impact speeds, be transformed to a modified form. This transformation is accomplished by using alternative formulas to calculate Vrel for each case in the Radar Brake Algorithm. Separate probability distributions are then calculated for these alternative values of Vrel, referred to as the "modified" Vrel. A more thorough analysis of the details and rationale for this procedure is presented as Appendix L. Section 4.1 of this report presents intermediate results of the computations including the Vrel data computed. Section 4.2 presents the actual benefit computations.

4.4.1 Computational Results

The presence of missing and/or inconsistent data in the North Carolina accident data file, together with the impossibility of properly analyzing cases not fitting appropriate patterns, results in a large fraction of the original accident involvements being unclassified by KRAESP accident configurations (KSPTYP) or by BRAKE accident configuration (CONFIG) and/or results in Vrel being unknown. Table 4-6 presents a summary of the disposition of cases according to KSPTYP, CONFIG, the value of Vrel, and whether or not the case vehicle was a passenger car. It may be noted that the avoidance of accidents by the operation of a radar brake system results in reassignment of cases from the Vrel=known category to Vrel=0.

Mitigation in the severity of accidents which are not avoided is reflected in a shift in the Vrel probability distribution. These distributions are computed only for the subset of accident involvements for which Vrel and the accident

TABLE 4-6. DISPOSITION OF CASES BY ACCIDENT TYPE, ACCIDENT CONFIGURATION, AND RADAR SYSTEM

System 1 (Baseline), Unmodified Vrel

KRAESP Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Fixed-Object Front	6,672	0	5	0
Fixed-Object Side	3,034	0	2	0
Rollover	4,140	0	0	0
Vehicle-to-Vehicle Front	34,825	0	127	0
Vehicle-to-Vehicle Side	30,685	0	12	0
Vehicle-to-Vehicle Rear	6,033	0	105	0
Non-Motorists	3,396	0	27	0
Unknown	7,747	0	1	111,332
Non-Passenger Cars				
Fixed-Object Front	1,433	0	1	0
Fixed-Object Side	470	0	0	0
Rollover	1,689	0	0	0
Vehicle-to-Vehicle Front	7,403	0	22	0
Vehicle-to-Vehicle Side	5,270	0	1	0
Vehicle-to-Vehicle Rear	1,502	0	28	0
Non-Motorists	616	0	1	0
Unknown	2,209	0	0	25,436

TABLE 4-6 (continued)

System 1 (Baseline), Unmodified Vrel (continued)

BRAKE Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Null	75,878	0	230	111,332
Rear End	4,036	0	31	0
Head-On	524	0	2	0
Fixed-Object	4,566	0	3	0
Right-to-Left Crossing	7,094	0	8	0
Left-to-Right Crossing	4,437	0	5	0
Non-Passenger Cars				
Null	16,131	0	48	25,436
Rear End	1,031	0	2	0
Head-On	97	0	0	0
Fixed-Object	1,033	0	0	0
Right-to-Left Crossing	1,421	0	1	0
Left-to-Right Crossing	880	0	1	0

TABLE 4-6 (continued)

System 1 (Baseline), Modified Vrel

KRAESP Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Fixed-Object Front	6,672	0	5	0
Fixed-Object Side	3,034	0	2	0
Rollover	4,134	3	4	0
Vehicle-to-Vehicle Front	32,938	1,470	545	0
Vehicle-to-Vehicle Side	28,713	811	173	0
Vehicle-to-Vehicle Rear	5,049	426	663	0
Non-Motorists	3,397	0	26	0
Unknown	6,937	730	82	111,332
Non-Passenger Cars				
Fixed-Object Front	1,433	0	1	0
Fixed-Object Side	467	0	3	0
Rollover	1,689	1	0	0
Vehicle-to-Vehicle Front	6,728	555	143	0
Vehicle-to-Vehicle Side	5,007	232	32	0
Vehicle-to-Vehicle Rear	1,250	127	153	0
Non-Motorists	616	0	1	0
Unknown	2,020	162	27	25,436

TABLE 4-6 (continued)

System 1 (Baseline), Modified Vrel (continued)

BRAKE Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Null	72,091	1,939	1,080	111,332
Rear End	3,525	153	389	0
Head-On	510	14	2	0
Fixed-Object	4,364	201	3	0
Right-to-Left Crossing	6,995	92	15	0
Left-to-Right Crossing	4,391	40	11	0
Non-Passenger Cars				
Null	15,030	893	256	25,436
Rear End	887	47	98	0
Head-On	95	2	0	0
Fixed-Object	922	110	0	0
Right-to-Left Crossing	1,404	14	4	0
Left-to-Right Crossing	869	11	1	0

TABLE 4-6 (continued)

System 2, Unmodified Vrel

KRAESP Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Fixed-Object Front	5,962	0	714	0
Fixed-Object Side	3,034	0	2	0
Rollover	4,134	0	6	0
Vehicle-to-Vehicle Front	28,226	0	6,727	0
Vehicle-to-Vehicle Side	29,5791	0	1,118	0
Vehicle-to-Vehicle Rear	3,062	0	3,076	0
Non-Motorists	2,938	0	486	0
Unknown	6,189	0	1,560	111,332
Non-Passenger Cars				
Fixed-Object Front	1,195	0	238	0
Fixed-Object Side	470	0	0	0
Rollover	1,684	0	5	0
Vehicle-to-Vehicle Front	5,970	0	1,456	0
Vehicle-to-Vehicle Side	5,010	0	2261	0
Vehicle-to-Vehicle Rear	849	0	680	0
Non-Motorists	508	0	109	0
Unknown	1,923	0	286	25,436

TABLE 4-6 (continued)

System 2, Unmodified Vrel (continued)

BRAKE Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Null	70,225	0	5,886	111,332
Rear End	769	0	3,298	0
Head-On192	0	334	0	
Fixed-Object	1,594	0	2,975	0
Right-to-Left Crossing	6,312	0	790	0
Left-to-Right Crossing	4,033	0	409	0
Non-Passenger Cars				
Null	14,925	0	1,254	25,436
Rear End	220	0	813	0
Head-On	48	0	49	0
Fixed-Object	354	0	679	0
Right-to-Left Crossing	1,262	0	160	0
Left-to-Right Crossing	802	0	78	0

TABLE 4-6 (continued)

System 2, Modified Vrel

KRAESP Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Fixed-Object Front	5,962	0	714	0
Fixed-Object Side	3,034	0	2	0
Rollover	4,128	3	10	0
Vehicle-to-Vehicle Front	26,668	1,421	6,863	0
Vehicle-to-Vehicle Side	28,591	821	1,285	0
Vehicle-to-Vehicle Rear	2,385	425	3,327	0
Non-Motorists	2,938	0	485	0
Unknown	5,438	670	1,640	111,332
Non-Passenger Cars				
Fixed-Object Front	1,195	0	238	0
Fixed-Object Side	467	0	3	0
Rollover	1,684	1	5	0
Vehicle-to-Vehicle Front	5,406	519	1,501	0
Vehicle-to-Vehicle Side	4,728	247	295	0
Vehicle-to-Vehicle Rear	656	129	745	0
Non-Motorists	508	0	109	0
Unknown	1,752	144	313	25,436

TABLE 4-6 (continued)

System 2, Modified Vrel (continued)

BRAKE Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Null	66,793	2,885	6,432	111,332
Rear End	535	168	3,364	0
Head-On	173	18	335	0
Fixed-Object	1,469	125	2,975	0
Right-to-Left Crossing	6,199	97	806	0
Left-to-Right Crossing	3,980	47	415	0
Non-Passenger Cars				
Null	13,882	893	1,405	25,436
Rear End	168	32	834	0
Head-On	41	7	49	0
Fixed-Object	284	70	679	0
Right-to-Left Crossing	1,244	15	163	0
Left-to-Right Crossing	779	23	79	0

TABLE 4-6 (continued)

System 3, Unmodified Vrel

KRAESP Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Fixed-Object Front	6,599	0	77	0
Fixed-Object Side	3,034	0	2	0
Rollover	4,135	0	5	0
Vehicle-to-Vehicle Front	29,901	0	5,052	0
Vehicle-to-Vehicle Side	29,652	0	1,045	0
Vehicle-to-Vehicle Rear	4,575	0	1,563	0
Non-Motorists	3,002	0	421	0
Unknown	6,265	0	1,484	111,332
Non-Passenger Cars				
Fixed-Object Front	1,326	0	107	0
Fixed-Object Side	470	0	0	0
Rollover	1,686	0	3	0
Vehicle-to-Vehicle Front	6,386	0	1,039	0
Vehicle-to-Vehicle Side	5,025	0	246	0
Vehicle-to-Vehicle Rear	1,148	0	382	0
Non-Motorists	522	0	94	0
Unknown	1,941	0	269	25,436

TABLE 4-6 (continued)

System 3, Unmodified Vrel (continued)

BRAKE Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Null	71,890	0	4,217	111,332
Rear End	2,318	0	1,749	0
Head-On	193	0	333	0
Fixed-Object	2,344	0	2,225	0
Right-to-Left Crossing	6,361	0	741	0
Left-to-Right Crossing	4,059	0	383	0
Non-Passenger Cars				
Null	15,259	0	921	25,436
Rear End	600	0	433	0
Head-On	47	0	49	0
Fixed-Object	518	0	515	0
Right-to-Left Crossing	1,273	0	149	0
Left-to-Right Crossing	808	0	72	0

TABLE 4-6 (continued)

System 3, Modified Vrel

KRAESP Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Fixed-Object Front	6,599	0	77	0
Fixed-Object Side	3,034	0	2	0
Rollover	4,128	3	9	0
Vehicle-to-Vehicle Front	28,136	1,750	5,067	0
Vehicle-to-Vehicle Side	28,629	862	1,206	0
Vehicle-to-Vehicle Rear	3,758	578	1,802	0
Non-Motorists	3,003	0	420	0
Unknown	5,486	761	1,502	111,332
Non-Passenger Cars				
Fixed-Object Front	1,326	0	107	0
Fixed-Object Side	467	0	3	0
Rollover	1,686	1	3	0
Vehicle-to-Vehicle Front	5,768	597	1,061	0
Vehicle-to-Vehicle Side	4,741	249	281	0
Vehicle-to-Vehicle Rear	932	151	447	0
Non-Motorists	522	0	94	0
Unknown	1,763	160	286	25,436

TABLE 4-6 (continued)

System 3, Modified Vrel (continued)

BRAKE Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Null	68,252	3,172	4,686	111,332
Rear End	1,954	307	1,806	0
Head-On	170	23	333	0
Fixed-Object	2,178	273	2,118	0
Right-to-Left Crossing	6,228	119	755	0
Left-to-Right Crossing	3,994	59	388	0
Non-Passenger Cars				
Null	14,184	932	1,064	25,436
Rear End	512	69	452	0
Head-On	40	7	49	0
Fixed-Object	438	100	495	0
Right-to-Left Crossing	1,248	24	149	0
Left-to-Right Crossing	783	24	73	0

TABLE 4-6 (continued)

System 4, Unmodified Vrel

KRAESP Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Fixed-Object Front	6,599	0	77	0
Fixed-Object Side	3,034	0	2	0
Rollover	4,133	0	7	0
Vehicle-to-Vehicle Front	28,453	0	6,500	0
Vehicle-to-Vehicle Side	29,976	0	721	0
Vehicle-to-Vehicle Rear	2,472	0	3,666	0
Non-Motorists	2,961	0	462	0
Unknown	6,263	0	1,485	111,332
Non-Passenger Cars				
Fixed-Object Front	1,326	0	107	0
Fixed-Object Side	469	0	1	0
Rollover	1,684	0	6	0
Vehicle-to-Vehicle Front	5,968	0	1,458	0
Vehicle-to-Vehicle Side	5,112	0	159	0
Vehicle-to-Vehicle Rear	701	0	829	0
Non-Motorists	511	0	105	0
Unknown	1,940	0	269	25,436

TABLE 4-6 (continued)

System 4, Unmodified Vrel (continued)

BRAKE Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Null	70,113	0	5,994	111,332
Rear End	195	0	3,872	0
Head-On	492	0	34	0
Fixed-Object	2,344	0	2,225	0
Right-to-Left Crossing	6,563	0	539	0
Left-to-Right Crossing	4,186	0	256	0
Non-Passenger Cars				
Null	14,895	0	1,284	25,436
Rear End	40	0	993	0
Head-On	89	0	8	0
Fixed-Object	518	0	515	0
Right-to-Left Crossing	1,327	0	95	0
Left-to-Right Crossing	841	0	39	0

TABLE 4-6 (continued)

System 4, Modified Vrel

KRAESP Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Fixed-Object Front	6,599	0	77	0
Fixed-Object Side	3,034	0	2	0
Rollover	4,126	3	11	0
Vehicle-to-Vehicle Front	26,920	1,548	6,485	0
Vehicle-to-Vehicle Side	28,922	880	895	0
Vehicle-to-Vehicle Rear	1,932	342	3,864	0
Non-Motorists	2,962	0	462	0
Unknown	5,483	762	1,504	111,332
Non-Passenger Cars				
Fixed-Object Front	1,326	0	107	0
Fixed-Object Side	466	0	4	0
Rollover	1,683	1	6	0
Vehicle-to-Vehicle Front	5,413	543	1,469	0
Vehicle-to-Vehicle Side	4,828	248	195	0
Vehicle-to-Vehicle Rear	536	112	882	0
Non-Motorists	511	0	105	0
Unknown	1,762	160	287	25,436

TABLE 4-6 (continued)

System 4, Modified Vrel (continued)

BRAKE Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Null	66,718	2,956	6,435	111,332
Rear End	99	79	3,889	0
Head-On	466	79	3,889	0
Fixed-Object	2,178	273	2,118	0
Right-to-Left Crossing	6,397	143	562	0
Left-to-Right Crossing	4,122	57	263	0
Non-Passenger Cars				
Null	13,873	891	1,415	25,436
Rear End	19	16	998	0
Head-On	81	8	8	0
Fixed-Object	438	100	495	0
Right-to-Left Crossing	1,297	25	99	0
Left-to-Right Crossing	818	23	40	0

TABLE 4-6 (continued)

System 5, Unmodified Vrel

KRAESP Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Fixed-Object Front	6,599	0	77	0
Fixed-Object Side	3,034	0	2	0
Rollover	4,133	0	7	0
Vehicle-to-Vehicle Front	28,267	0	6,686	0
Vehicle-to-Vehicle Side	29,976	0	721	0
Vehicle-to-Vehicle Rear	2,472	0	3,666	0
Non-Motorists	2,945	0	478	0
Unknown	6,263	0	1,485	111,332
Non-Passenger Cars				
Fixed-Object Front	1,326	0	107	0
Fixed-Object Side	469	0	1	0
Rollover	1,684	0	6	0
Vehicle-to-Vehicle Front	5,946	0	1,479	0
Vehicle-to-Vehicle Side	5,112	0	159	0
Vehicle-to-Vehicle Rear	701	0	829	0
Non-Motorists	508	0	108	0
Unknown	1,940	0	269	25,436

TABLE 4-6 (continued)

System 5, Unmodified Vrel (continued)

BRAKE Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Null	71,113	0	5,995	111,332
Rear End	195	0	3,872	0
Head-On	291	0	235	0
Fixed-Object	2,344	0	2,225	0
Right-to-Left Crossing	6,563	0	539	0
Left-to-Right Crossing	4,186	0	256	0
Non-Passenger Cars				
Null	14,895	0	1,284	25,436
Rear End	40	0	993	0
Head-On	64	0	33	0
Fixed-Object	518	0	515	0
Right-to-Left Crossing	1,327	0	95	0
Left-to-Right Crossing	841	0	39	0

TABLE 4-6 (continued)

System 5, Modified Vrel

KRAESP Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Fixed-Object Front	6,599	0	77	0
Fixed-Object Side	3,034	0	2	0
Rollover	4,126	3	11	0
Vehicle-to-Vehicle Front	26,683	1,590	6,679	0
Vehicle-to-Vehicle Side	28,922	880	895	0
Vehicle-to-Vehicle Rear	1,932	342	2,864	0
Non-Motorists	2,946	0	477	0
Unknown	5,483	762	1,504	111,332
Non-Passenger Cars				
Fixed-Object Front	1,326	0	107	0
Fixed-Object Side	466	0	4	0
Rollover	1,683	1	6	0
Vehicle-to-Vehicle Front	5,385	546	1,494	0
Vehicle-to-Vehicle Side	4,828	248	195	0
Vehicle-to-Vehicle Rear	536	112	882	0
Non-Motorists	508	0	108	0
Unknown	1,762	160	287	25,436

TABLE 4-6 (continued)

System 5, Modified Vrel (continued)

BRAKE Configuration	Vrel Known	Vrel Less Than 0	Vrel = 0	Vrel Unknown
Passenger Cars				
Null	66,716	2,958	6,436	111,332
Rear End	99	79	3,889	0
Head-On	216	66	243	0
Fixed-Object	2,178	273	562	0
Right-to-Left Crossing	5,397	143	562	0
Left-to-Right Crossing	4,122	57	263	0
Non-Passenger Cars				
Null	13,873	891	1,415	25,436
Rear End	19	16	998	0
Head-On	49	11	37	0
Fixed-Object	438	100	495	0
Right-to-Left Crossing	1,297	25	99	0
Left-to-Right Crossing	818	23	40	0

configuration are known. Table 4-7 tabulates the actual distributions for passenger car cases by KRAESP configuration and radar system for both modified and unmodified Vrel values. Figures 4-17 through 4-26 present these results graphically.

Since a large fraction of the North Carolina cases are not used to estimated the radar system performance due to insufficient information, it is important to consider whether any bias is introduced by this factor. Table 4-8 contains univariate frequency distributions for several variables for a sample of the cases where accident configuration and Vrel were known, compared to a sample of cases for unknown configuration and Vrel, which were excluded from the analysis.

The set of cases which had unknown results show a higher frequency of Most Severe Injury, but the distributions over Estimated Travel Speed and Estimated Impact Speed are very similar for known and unknown data, given proportions only over the cases for which the speeds are known. Vehicle Types involved and Road Conditions also show essentially no difference between the two sets of cases. From the point of view of accident reconstruction, vehicle speeds, vehicle types, and road conditions are the most critical elements to consider. Occupant injury is estimated indirectly from speeds (specifically Vrel), so discrepancies in actual case injuries in the sets of known and unknown data are not of direct concern. Accident configurations cannot, of course, be compared because this is, by definition, unknown in the set of "unknown" data.

4.4.2 Benefits Calculations

The Kinetic Research Accident Simulation and Project Model (KRAESP; Refs. 17, 18, and 20) has been used to compute predicted fatalities and injuries by AIS level for the accident sample in question.

In order to validate the KRAESP projections, the baseline accident injuries were tabulated by KRAESP accident configuration and AIS level. KRAESP input data concerning number of accidents by accident configuration and vehicle occupancy by seat position and impact mode were adjusted to get good agreement with the actual data. Table 4-9 shows the actual and the predicted baseline injuries and

TABLE 4-7. PROBABILITY OF VREL BY ACCIDENT CONFIGURATION AND RADAR SYSTEM FOR PASSENGER CARS WITH KNOWN ACCIDENT CONFIGURATION AND KNOWN VREL*

(a) Fixed Object Front

	Baseline		System 2		Systems 3,4,5	
Vrel	U	M	U	M	U	M
1-5	0.012	0.050	0.013	0.125	0.016	0.140
6-10	0.037	0.265	0.111	0.267	0.064	0.339
11-15	0.050	0.439	0.042	0.382	0.097	0.318
16-20	0.116	0.318	0.118	0.176	0.204	0.159
21-25	0.099	0.159	0.107	0.034	0.085	0.031
16-30	0.158	0.031	0.140	0.031	0.121	0.013
31-35	0.163	0.013	0.131	0.013	0.108	0.001
36-40	0.120	0.001	0.113	0.001	0.102	0.000
41-45	0.086		0.076		0.070	
46-50	0.080		0.074		0.067	
51-55	0.066		0.027		0.024	
56-60	0.024		0.027		0.024	
61-65	0.024		0.008		0.007	
66-70	0.007		0.007		0.006	
71-75	0.006		0.004		0.004	
76-80	0.004		0.004		0.003	
81-85	0.003		0.001		0.000	
86-90	0.000		0.001		0.001	
91-95	0.001		0.000		0.000	
96-100	0.001		0.000		0.000	

U = unmodified; M = modified.

TABLE 4-7 (continued)

(b) Fixed Object Side

Vrel	All Systems U	M
1-5	0.015	0.093
6-10	0.037	0.340
11-15	0.041	0.368
16-20	0.093	0.164
21-25	0.092	0.027
16-30	0.157	0.007
31-35	0.143	
36-40	0.133	
41-45	0.092	
46-50	0.010	
51-55	0.040	
56-60	0.023	
61-65	0.014	
66-70	0.010	
71-75	0.004	
76-80	0.005	
81-85	0.000	
86-90	0.002	
91-95	0.000	
96-100	0.000	

U = unmodified; M = modified.

TABLE 4-7 (continued)

(c) Vehicle-to-Vehicle Front

	Baseline		System 2		System 3		System 4		System 5	
Vrel	U	M	U	M	U	M	U	M	U	M
1-5	0.047	0.184	0.036	0.175	0.049	0.189	0.035	0.175	0.035	0.177
6-10	0.073	0.224	0.060	0.211	0.074	0.211	0.057	0.204	0.058	0.204
11-15	0.091	0.219	0.087	0.217	0.091	0.215	0.085	0.216	0.087	0.217
16-20	0.105	0.153	0.102	0.163	0.109	0.159	0.099	0.164	0.101	0.165
21-25	0.167	0.101	0.164	0.113	0.159	0.109	0.167	0.112	0.167	0.112
16-30	0.128	0.058	0.133	0.059	0.126	0.057	0.132	0.062	0.133	0.062
31-35	0.118	0.030	0.123	0.032	0.116	0.032	0.122	0.033	0.123	0.033
36-40	0.102	0.011	0.105	0.012	0.099	0.011	0.108	0.012	0.108	0.012
41-45	0.056	0.008	0.065	0.009	0.062	0.009	0.064	0.010	0.064	0.009
46-50	0.048	0.005	0.050	0.004	0.047	0.004	0.053	0.005	0.052	0.004
51-55	0.021	0.004	0.023	0.003	0.021	0.003	0.023	0.004	0.022	0.003
56-60	0.016	0.002	0.019	0.002	0.018	0.002	0.020	0.002	0.019	0.002
61-65	0.007	0.001	0.008	0.000	0.008	0.000	0.009	0.000	0.008	0.000
66-70	0.006		0.008		0.007		0.008		0.008	
71-75	0.004		0.005		0.004		0.005		0.005	
76-80	0.003		0.004		0.003		0.004		0.004	
81-85	0.002		0.002		0.002		0.003		0.002	
86-90	0.002		0.002		0.002		0.003		0.002	
91-95	0.001		0.001		0.001		0.001		0.001	
96-100	0.002		0.002		0.002		0.002		0.002	

U = unmodified; M = modified.

TABLE 4-7 (continued)

(d) Vehicle-to-Vehicle Side

	Baseline		System 2		System 3		Systems 4&5	
Vrel	U	M	U	M	U	M	U	M
1-5	0.018	0.206	0.019	0.202	0.021	0.203	0.019	0.204
6-10	0.051	0.244	0.053	0.245	0.054	0.245	0.056	0.244
11-15	0.097	0.215	0.099	0.216	0.099	0.216	0.101	0.215
16-20	0.102	0.154	0.106	0.154	0.106	0.154	0.103	0.154
21-25	0.209	0.096	0.202	0.099	0.202	0.099	0.204	0.096
16-30	0.135	0.050	0.139	0.048	0.139	0.048	0.137	0.050
31-35	0.135	0.021	0.134	0.022	0.134	0.022	0.133	0.021
36-40	0.110	0.007	0.103	0.007	0.103	0.007	0.104	0.007
41-45	0.061	0.004	0.066	0.004	0.066	0.004	0.063	0.004
46-50	0.046	0.001	0.041	0.001	0.041	0.001	0.043	0.001
51-55	0.016	0.001	0.015	0.001	0.015	0.001	0.015	0.001
56-60	0.011	0.001	0.012	0.001	0.012	0.001	0.011	0.001
61-65	0.005		0.005		0.005		0.005	
66-70	0.002		0.002		0.002		0.002	
71-75	0.002		0.002		0.002		0.002	
76-80	0.001		0.001		0.001		0.001	
81-85	0.000		0.000		0.000		0.000	
86-90	0.000		0.000		0.000		0.000	
91-95	0.000		0.000		0.000		0.000	
96-100	0.000		0.000		0.000		0.000	

U = unmodified; M = modified.

TABLE 4-7 (continued)

(e) Vehicle-to-Vehicle Rear

	Baseline		System 2		System 3		Systems 4&5	
Vrel	U	M	U	M	U	M	U	M
1-5	0.216	0.288	0.226	0.358	0.231	0.355	0.247	0.341
6-10	0.234	0.224	0.232	0.235	0.262	0.232	0.209	0.203
11-15	0.167	0.190	0.177	0.181	0.165	0.194	0.151	0.187
16-20	0.126	0.116	0.114	0.105	0.136	0.102	0.106	0.119
21-25	0.106	0.083	0.109	0.064	0.100	0.059	0.118	0.077
16-30	0.067	0.052	0.055	0.033	0.046	0.030	0.064	0.041
31-35	0.040	0.020	0.042	0.010	0.031	0.013	0.050	0.015
36-40	0.021	0.010	0.019	0.005	0.012	0.005	0.023	0.007
41-45	0.009	0.005	0.009	0.005	0.006	0.005	0.011	0.007
46-50	0.005	0.004	0.008	0.001	0.005	0.002	0.010	0.002
51-55	0.002	0.003	0.004	0.001	0.002	0.001	0.005	0.001
56-60	0.001	0.003	0.002	0.002	0.001	0.001	0.002	0.002
61-65	0.001	0.001	0.001	0.000	0.001	0.000	0.002	0.000
66-70	0.001	0.001	0.001	0.000	0.001	0.000	0.001	0.001
71-75	0.001		0.001		0.001		0.001	
76-80	0.000		0.000		0.000		0.000	
81-85	0.000		0.000		0.000		0.000	
86-90	0.000		0.000		0.000		0.000	
91-95	0.000		0.000		0.000		0.000	
96-100	0.000		0.000		0.000		0.000	

U = unmodified; M = modified.

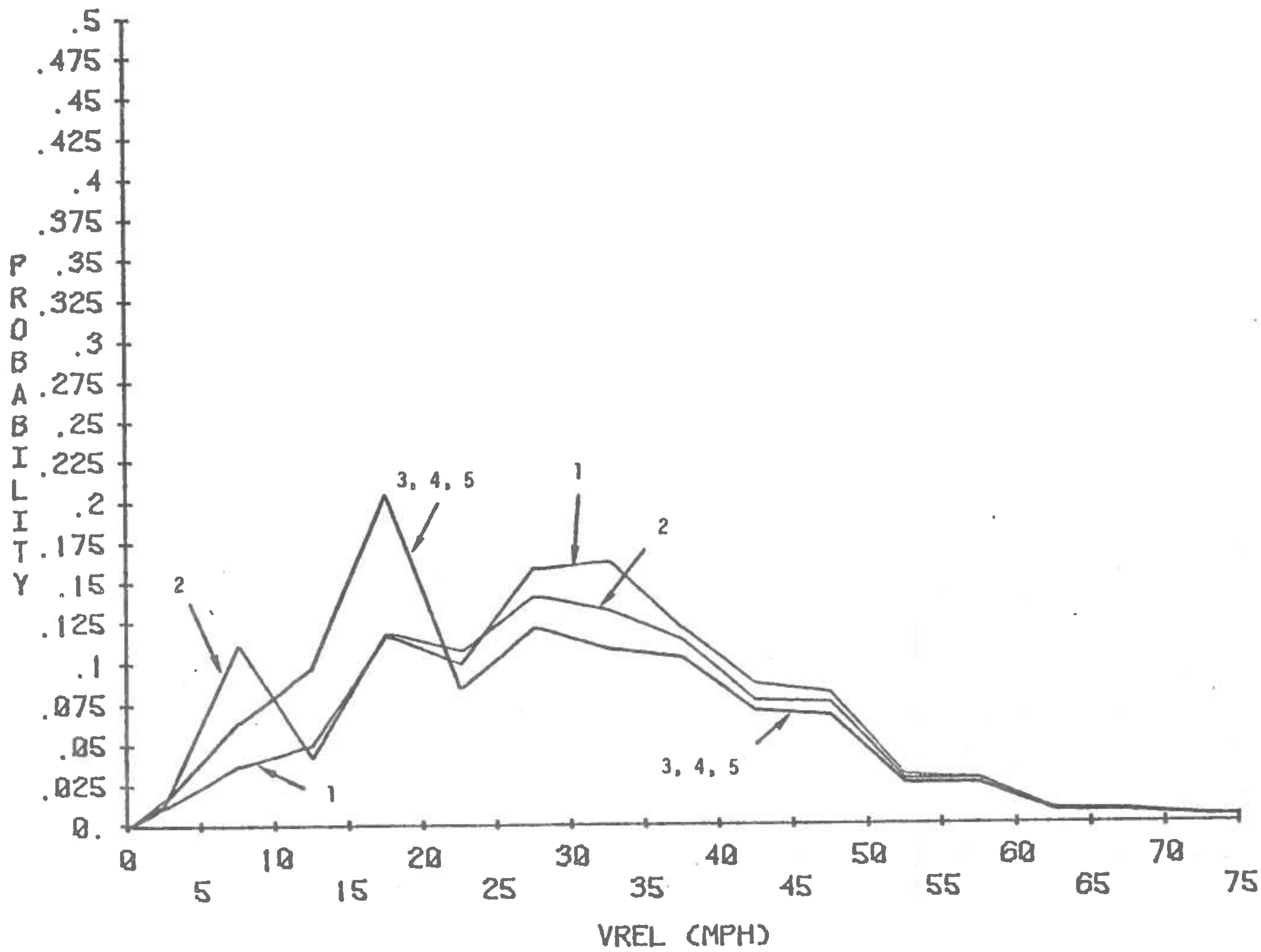


FIGURE 4-17. PROBABILITY OF VREL BY RADAR SYSTEM FOR FIXED OBJECT FRONT, UNMODIFIED VREL

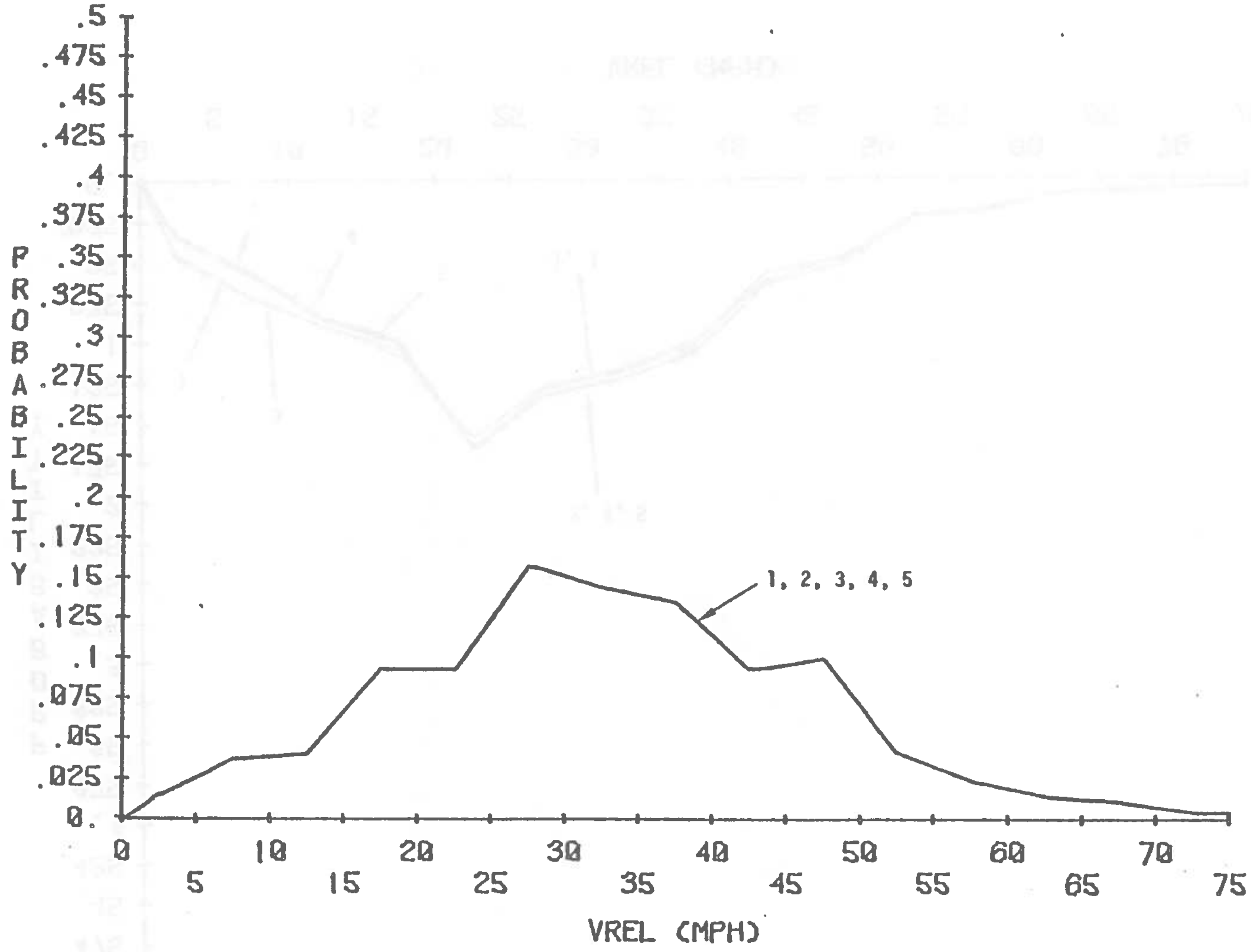


FIGURE 4-18. PROBABILITY OF VREL BY RADAR SYSTEM FOR FIXED OBJECT SIDE, UNMODIFIED VREL

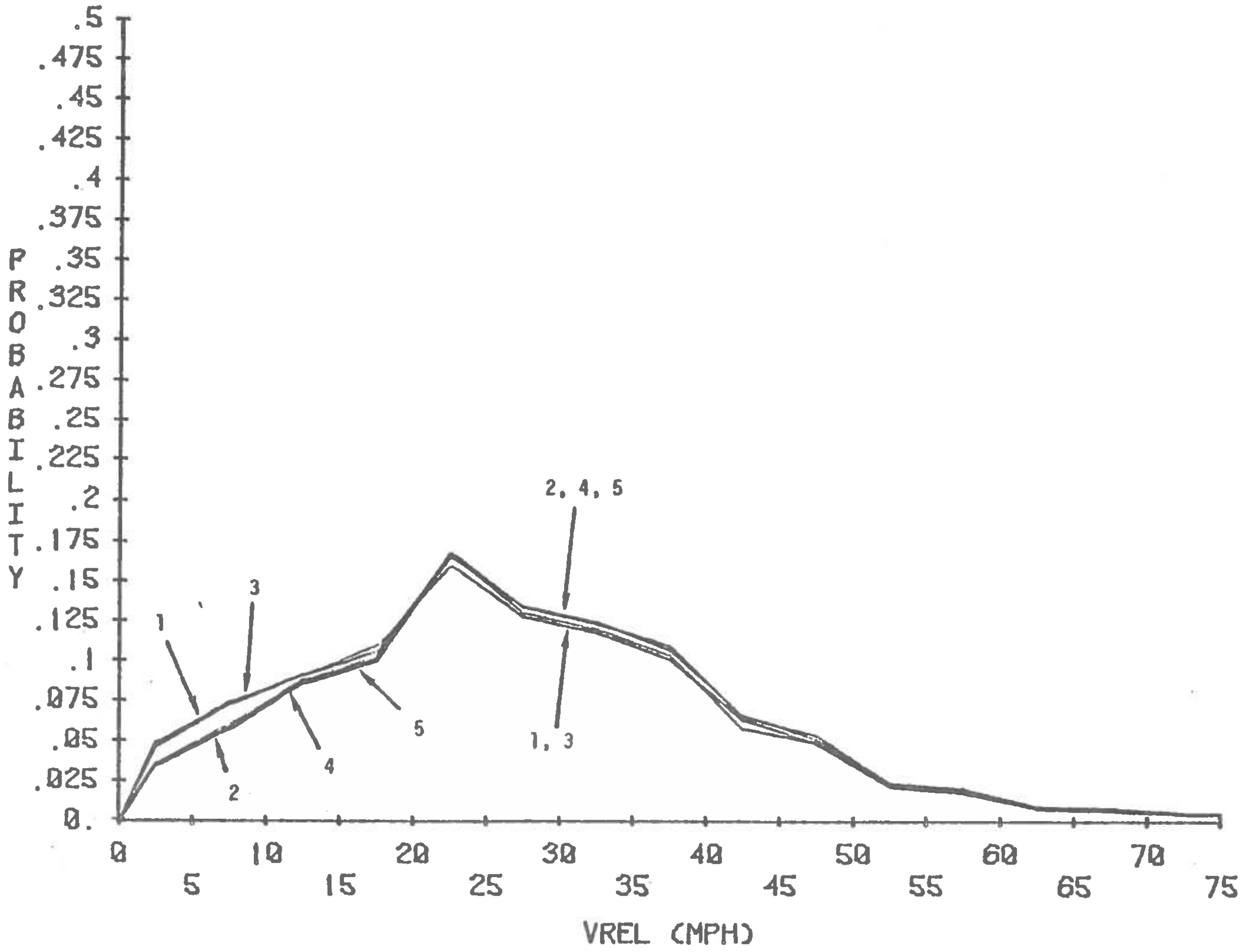


FIGURE 4-19. PROBABILITY OF VREL BY RADAR SYSTEM FOR VEHICLE-TO-VEHICLE FRONT, UNMODIFIED VREL

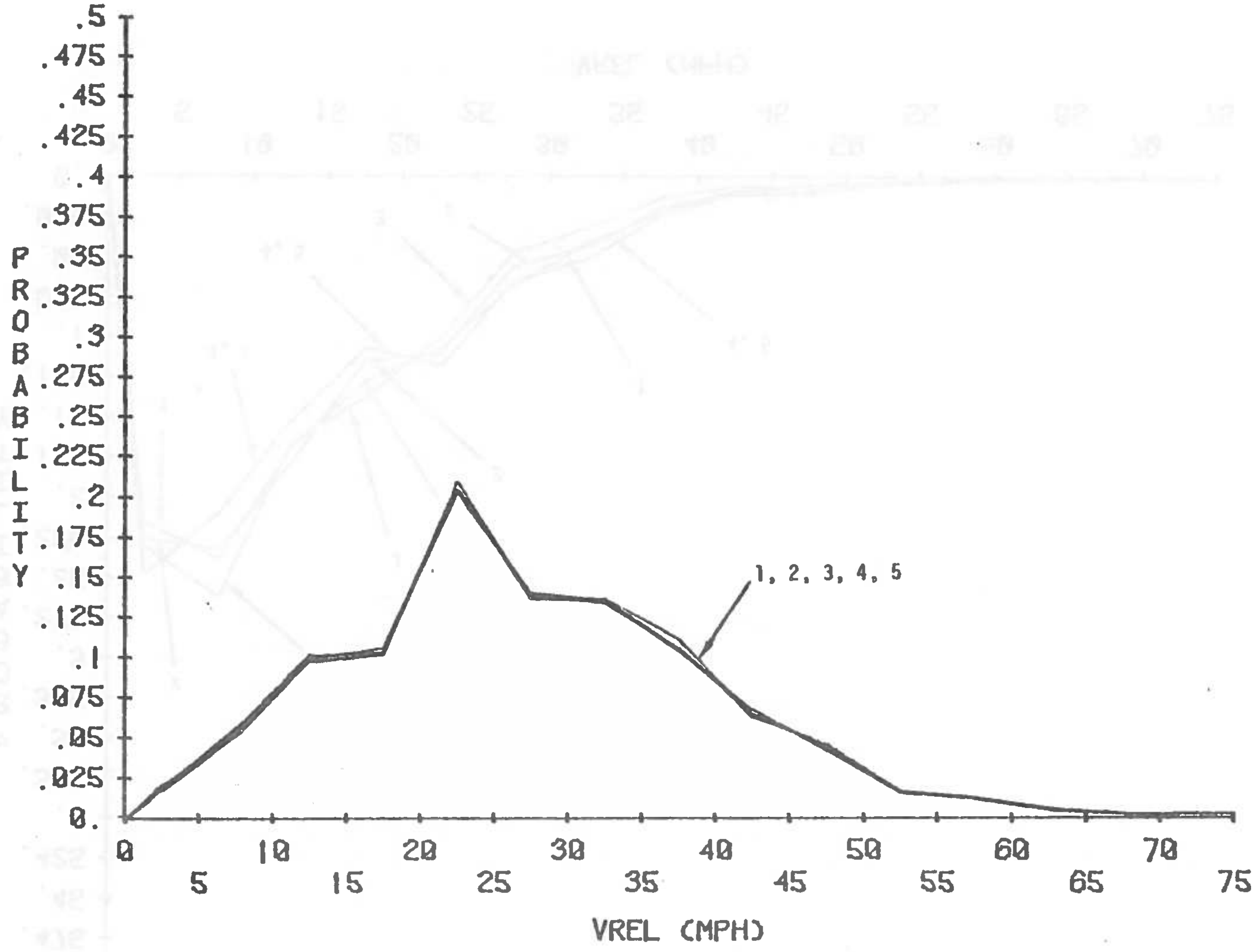


FIGURE 4-20. PROBABILITY OF VREL BY RADAR SYSTEM FOR VEHICLE-TO-VEHICLE SIDE, UNMODIFIED VREL

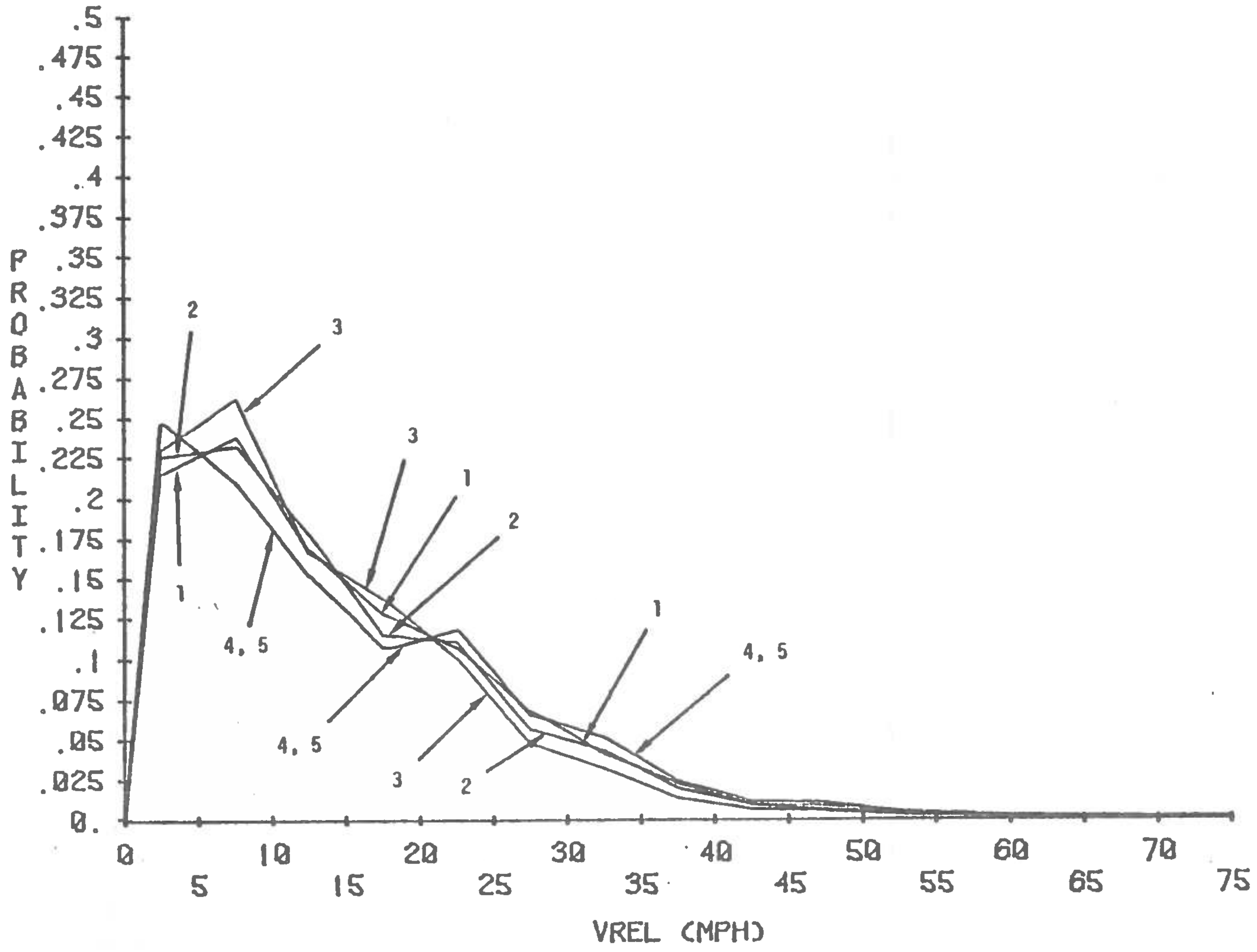


FIGURE 4-21. PROBABILITY OF VREL BY RADAR SYSTEM FOR VEHICLE-TO-VEHICLE REAR, UNMODIFIED VREL

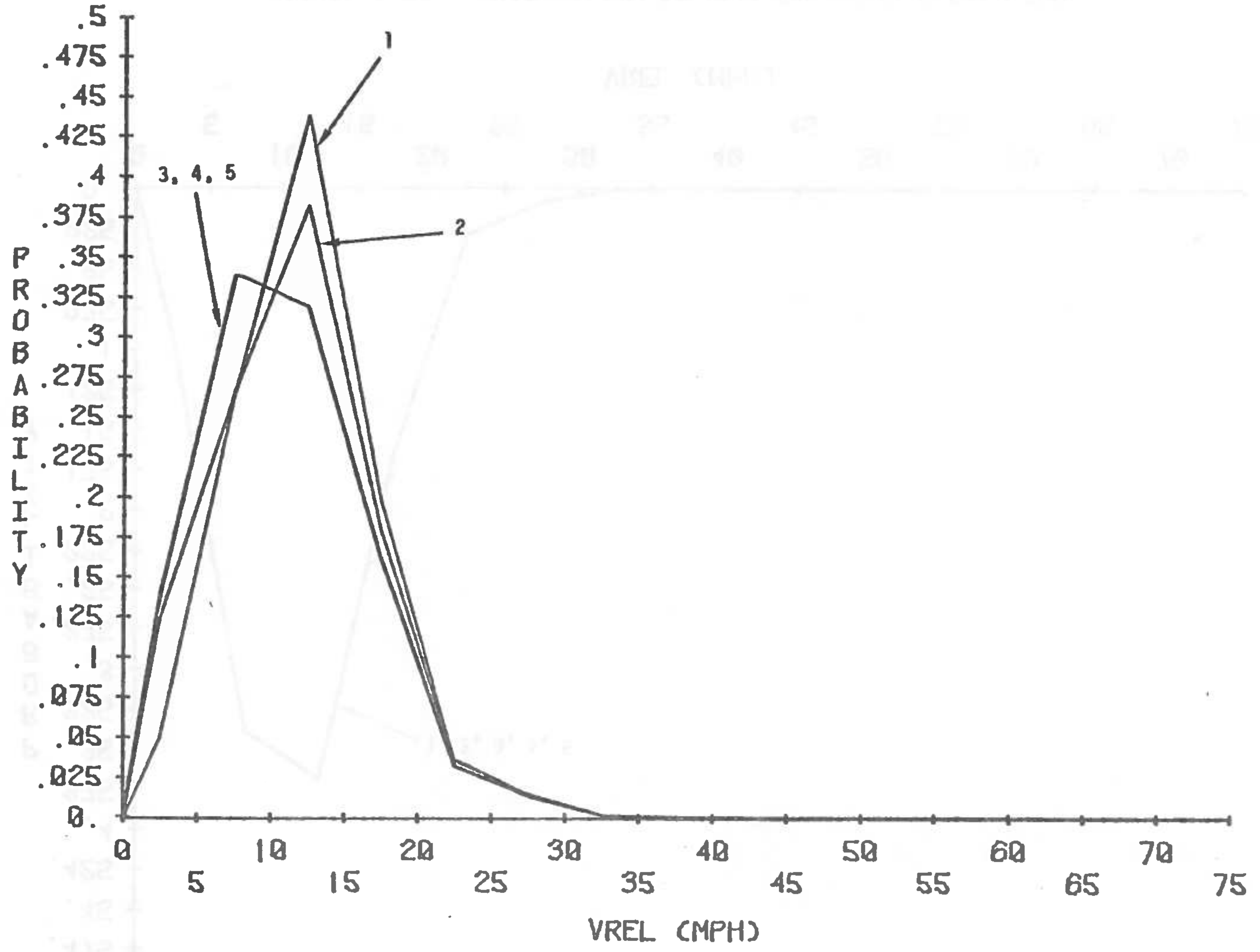


FIGURE 4-22. PROBABILITY OF VREL BY RADAR SYSTEM FOR FIXED OBJECT FRONT, MODIFIED VREL

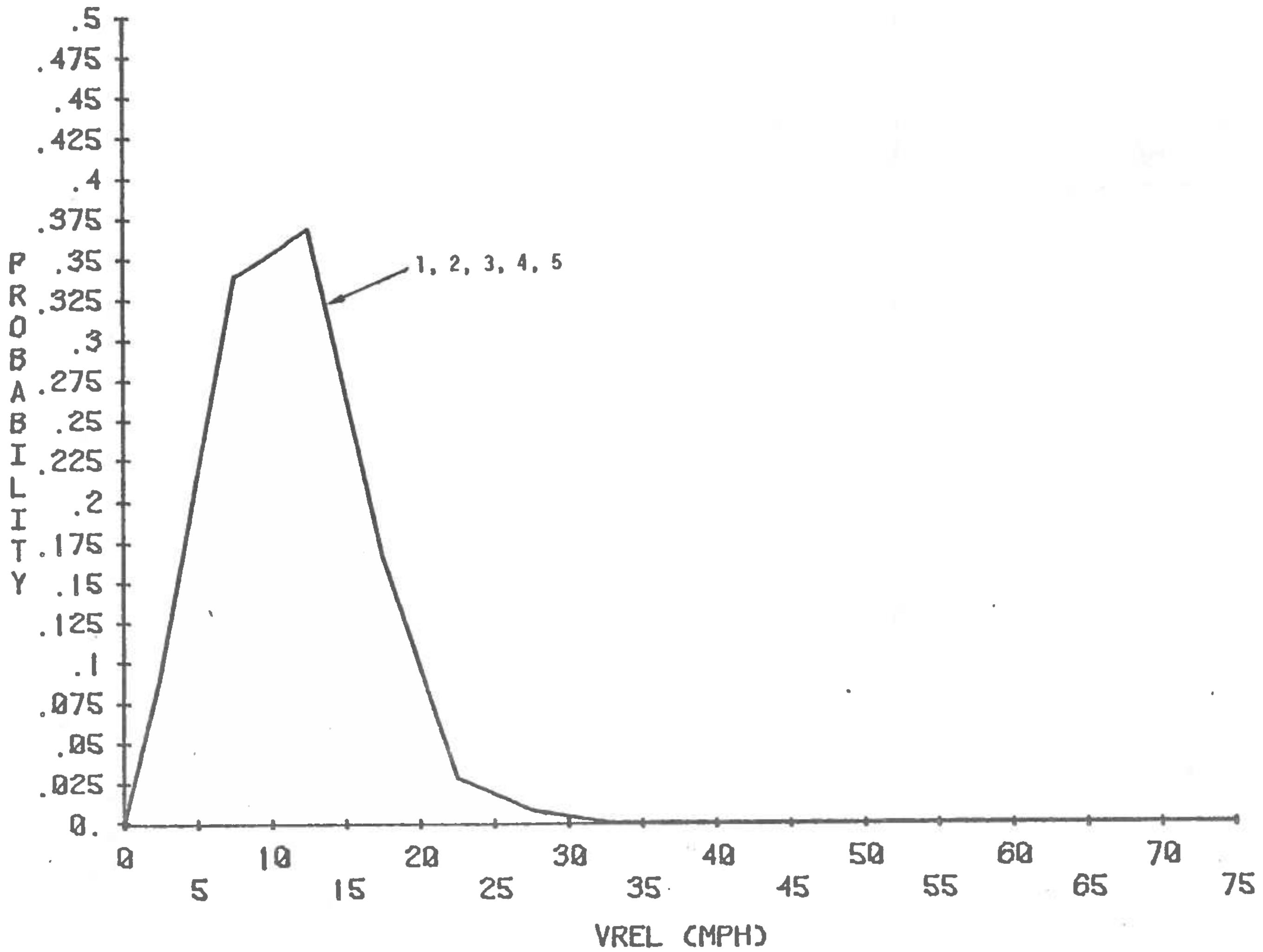


FIGURE 4-23. PROBABILITY OF VREL BY RADAR SYSTEM FOR FIXED OBJECT SIDE, MODIFIED VREL

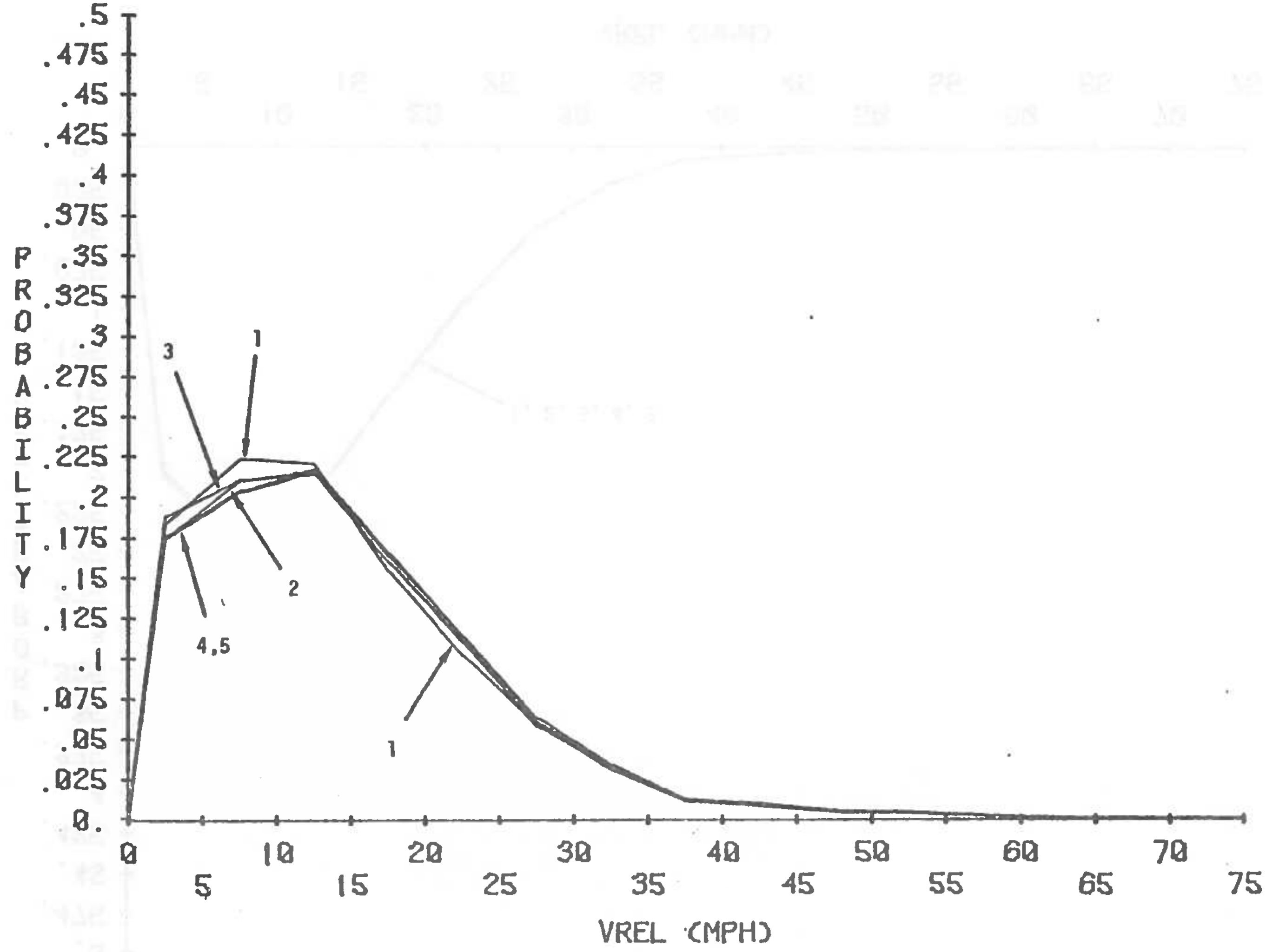


FIGURE 4-24. PROBABILITY OF VREL BY RADAR SYSTEM FOR VEHICLE-TO-VEHICLE FRONT, MODIFIED VREL

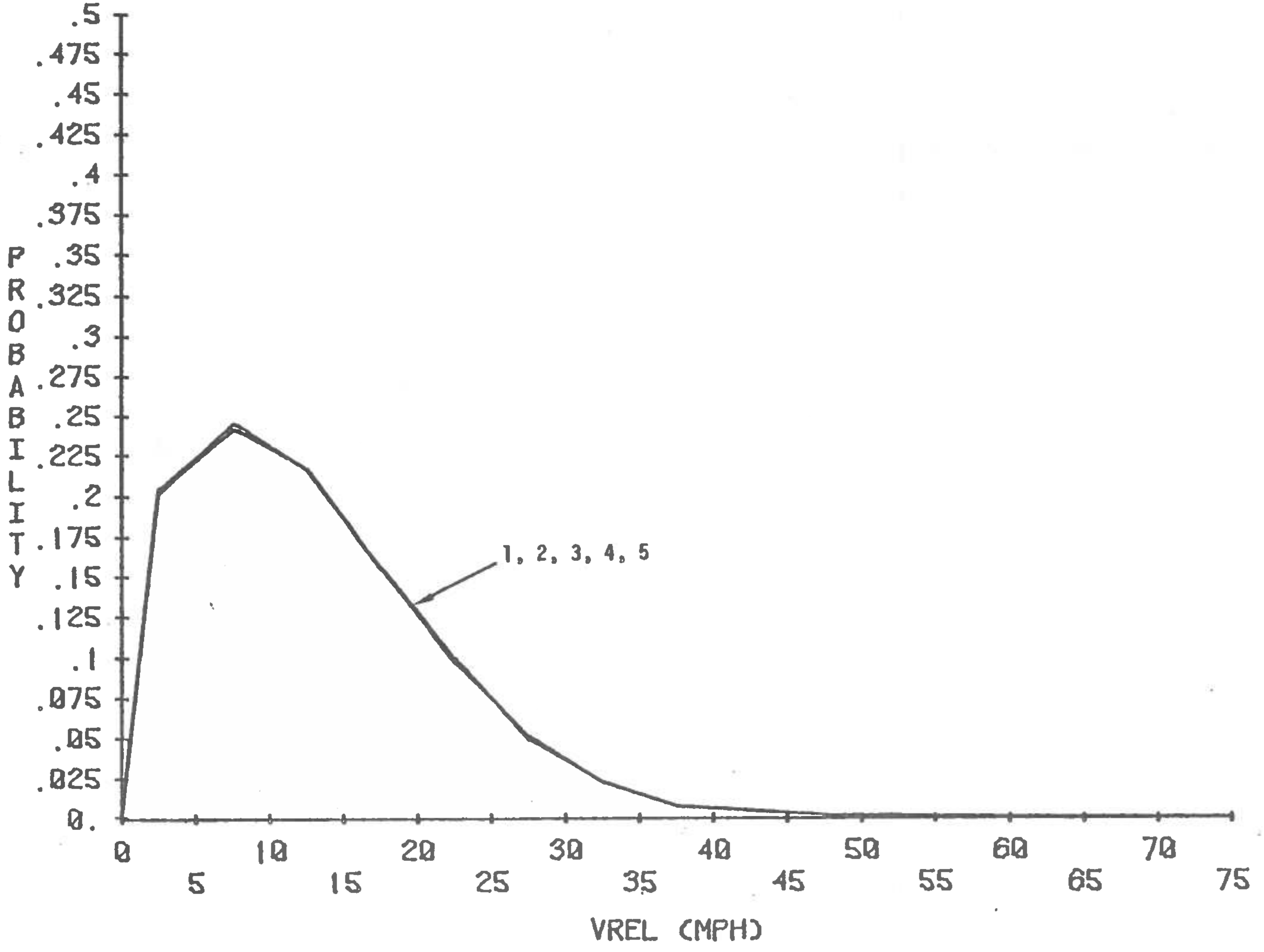


FIGURE 4-25. PROBABILITY OF VREL BY RADAR SYSTEM FOR VEHICLE-TO-VEHICLE SIDE, MODIFIED VREL

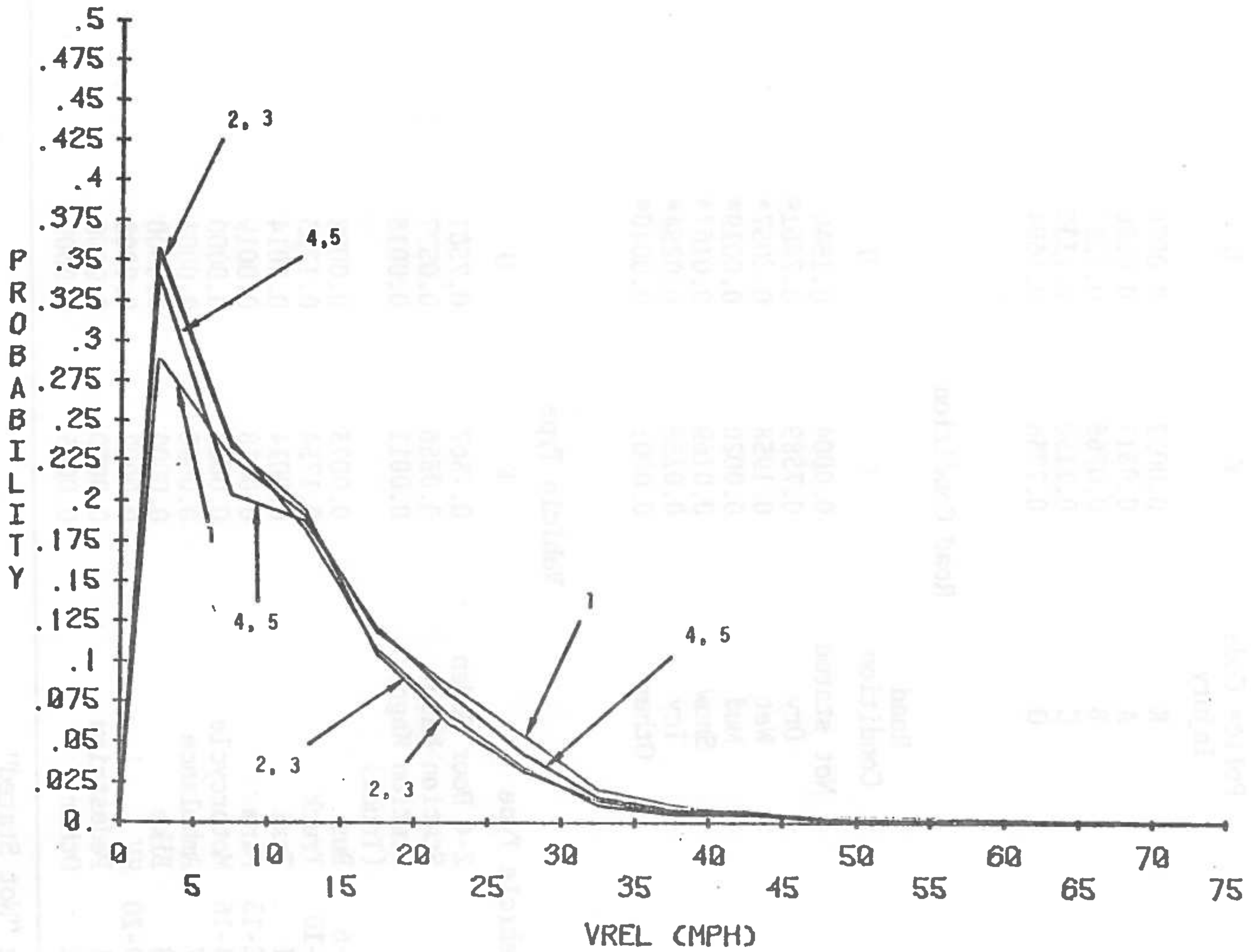


FIGURE 4-26. PROBABILITY OF VREL BY RADAR SYSTEM FOR VEHICLE-TO-VEHICLE REAR, MODIFIED VREL

TABLE 4-8. COMPARISON OF KNOWN CASES AND UNKNOWN CASES NORMALIZED FREQUENCY DISTRIBUTIONS

Most Severe Injury

Police Code Injury	K	U
K	0.0032	0.0078
A	0.0317	0.0686
B	0.0765	0.1297
C	0.1150	0.1335
O	0.7736	0.6604

Road Condition

Road Condition	K	U
Not stated	0.0004	0.1540
Dry	0.7589	0.7461*
Wet	0.1958	0.2057*
Mud	0.0020	0.0019*
Snow	0.0169	0.0167*
Icy	0.0258	0.0254*
Other	0.0001	0.0040*

Vehicle Type

Vehicle Type		K	U
1	2-4 Door Sedan	0.7567	0.7501
2	Station Wagon	0.0556	0.0577
3	Station Wagon (Truck)	0.0011	0.0018
4-6	Bus	0.0073	0.0098
7-10	Truck	0.1754	0.1753
11	Taxi	0.0014	0.0014
12-13	Farm	0.0018	0.0019
14-16	Motorcycle	0.0000	0.0000
17	Ambulance	0.0000	0.0003
18	Bike	0.0000	0.0000
19-20	RV	0.0002	0.0008
21	Pedestrian	0.0000	0.0000
22	Other	0.0005	0.0009

*Excluding "Not Stated"

TABLE 4-8 (continued)

Estimated Travel Speed

Speed (mph)	K	U
0	0.0011	0.0023
Unknown	0.0215	0.3491
1-10	0.1987	0.1895*
11-20	0.1499	0.1459*
21-30	0.1715	0.1757*
31-40	0.2096	0.2141*
41-50	0.1588	0.1687*
51-60	0.0823	0.0831*
61-70	0.0192	0.0122*
71-80	0.0069	0.0043*
81-90	0.0009	0.0010*
91-100	0.0010	0.0014*
101-110	0.0001	0.0007*

Estimated Impact Speed

Speed (mph)	K	U
0	0.0034	0.0019
Unknown	0.0191	0.4268
1-10	0.3065	0.2731*
11-20	0.2150	0.2141*
21-30	0.1957	0.1921*
31-40	0.1558	0.1642*
41-50	0.0862	0.1112*
51-60	0.0303	0.0367*
61-70	0.0081	0.0066*
71-80	0.0023	0.0014*
81-90	0.0002	0.0008*

*Excluding "Unknown"

TABLE 4-9. PREDICTED AND ACTUAL INJURIES FOR NORTH CAROLINA IN 1979 FOR THE BASELINE CASE

Accident Configuration	System	Injury Level (AIS)								Total Accident Involvements
		0	1	2	3	4	5	6	Total	
FOF	Actual	5,527	3,176	664	354	88	34	84	9,927	6,672
	System 1	5,547	3,003	899	335	56	35	55	9,929	6,672
FOS	Actual	3,068	1,102	225	115	28	11	58	4,607	3,034
	System 1	2,300	1,561	342	235	67	27	74	4,605	3,034
ROLLOVER	Actual	3,548	2,249	472	259	65	25	107	6,725	4,134
	System 1	3,119	1,847	1,066	416	54	37	188	6,728	4,134
VVF	Actual	41,576	9,806	1,723	697	155	56	126	54,139	32,938
	System 1	39,993	11,498	1,823	600	115	31	96	54,156	32,938
VVS	Actual	39,737	7,405	1,241	432	91	32	103	49,041	29,713
	System 1	36,135	10,333	1,263	892	154	58	195	49,029	29,713
VVR	Actual	8,468	1,522	218	65	11	3	3	10,290	5,049
	System 1	7,648	2,468	108	30	12	2	25	10,292	5,049
TOTAL	Actual	101,924	25,260	4,543	1,922	438	161	481	134,729	81,540
	System 1	94,742	30,710	5,501	2,508	458	190	633	134,729	81,540

fatalities by accident configuration for North Carolina in 1979. The actual data are based on those cases in the North Carolina file which were analyzed by the Radar Brake Algorithm. The projections are results of runs of the KRAESP Model using the modified Vrel distributions discussed in the previous section. The number of accidents specified for 1979 was 81,540, with 134,729 involved occupants.

The KRAESP input variables XPIM (probability of input by direction and mode) and XOF (seat position occupancy rate) were adjusted to give total numbers of actual data. The values used for XPIM are shown in Table 4-10, and the data used in XOF are shown in Table 4-11.

TABLE 4-10. VALUES USED FOR XPIM, BASELINE SYSTEM

Damage Area Clock Position	Vehicle-to-Vehicle	Fixed Object
1	0.13465	0.02727
2	0.06073	0.00620
3	0.06073	0.00620
4	0.06073	0.00620
5	0.02064	0.00000
6	0.02069	0.00000
7	0.02064	0.00000
8	0.06073	0.06620
9	0.06073	0.00620
10	0.06073	0.00620
11	0.13465	0.02727
12	0.13465	0.02727
13	0.00000	0.05070

TABLE 4-11. DATA USED IN XOF, BASELINE SYSTEM

Accident Configuration	Seat				Total
	LF	RF	LR	RR	
VVF	1.0	0.474	0.08	0.09	1.644
FOF	1.0	0.318	0.08	0.09	1.488
VVS	1.0	0.480	0.08	0.09	1.650
FOS	1.0	0.348	0.08	0.09	1.518
VVR	1.0	0.868	0.08	0.09	2.038
Rollover	1.0	0.457	0.08	0.09	1.627

In order to compute the comparison between KRAESP and North Carolina, it is finally necessary to convert the North Carolina injuries by police code to severity be overall AIS. A statistical relationship for this had been obtained previously (Ref. 21) from the NCSS file and is applied here. The relationship used is given in Table 4-12. The relationship is available by accident configuration separately, but was used only in the overall for the current application. The relationship is expressed below as a frequency of each AIS by categories of police coded injury. It may be noted that in these data and in the KRAESP model, all known fatalities have been recoded AIS 6 even though AIS 6 is not by definition synonymous with fatality.

The baseline injury distributions obtained in Table 4-9 are in fairly good agreement with the actual data. AIS 0 is somewhat under-represented, especially in fixed-object side impacts, and fatalities are somewhat over-represented. This could be corrected through further adjustment of the Vrel computation. The corrections that were made in this computation were rough in character. Furthermore, replication of NCSS characteristics, as in Reference 21, does not necessarily produce a suitable representation of North Carolina accidents.

As mentioned earlier, it was not possible to use NASS data because of the missing Delta-Vs and the pre-crash data. The basic KRAESP methodology is not the reason for the distortion seen in the injury distribution. It has resulted from the use

TABLE 4-12. PROBABILITY OF INJURY BY AIS AS A FUNCTION OF POLICE CODED INJURY*

Police Code	AIS 0	1	2	3	4	5	6**
K	0.00	0.00	0.00	0.00	0.00	0.00	1.00
A	0.00	0.47	0.23	0.20	0.06	0.03	0.01
B	0.10	0.73	0.13	0.04	0.01	0.00	0.00
C	0.35	0.57	0.05	0.02	0.00	0.00	0.00
O	0.93	0.06	0.01	0.00	0.00	0.00	0.00

*Data taken from NCSS.

**Category recoded to include all known fatalities.

of the adjusted North Carolina data file where Delta-Vs were not directly available. Hence, we ended up using NCSS-derived Delta-V versus AIS relationships. It would have been possible to convert Vrel values from the adjusted North Carolina data into Delta-V values using "Vindicator" programs that provide the weight estimates for the vehicles. However, it was not deemed feasible to undertake that within the time and dollar constraint of this program. The basic methodology of KRAESP is very sound and, with the use of consistent data, there would not have been any distortion.

Tables 4-13 through 4-16 tabulate the predicted injuries and fatalities for each of the radar systems. Table 4-17 details the values used in XPIM for each of the radar systems. Since radar braking avoids more accidents in some configurations than in others, it is necessary to adjust the impact probability distribution accordingly.

Table 4-18 shows the predicted non-motorist injuries and fatalities for the different radar systems. These results are based on the assumption that radar "sees" non-motorists in a manner comparable to metallic objects. If, as some experts believe, pedestrians, bicyclists, motorcyclists, etc., are not detectable by typical automotive radars at any useful range, then no benefits

TABLE 4-13. PREDICTED INJURIES AND FATALITIES FOR RADAR SYSTEM 2

	Impact Configuration						
AIS	FOF	FOS	Rollover	VVF	VVS	VVR	Total
0	5,091	2,302	3,114	32,193	34,741	3,709	81,150
1	2,636	1,562	1,845	9,456	9,970	1,088	25,667
2	748	342	1,065	1,513	1,223	43	4,934
3	277	235	416	495	862	10	2,295
4	47	68	54	93	149	5	416
5	78	27	37	24	56	0	172
6	45	74	188	73	189	6	575
Total	8,872	4,609	6,718	43,847	47,190	4,860	116,096

TABLE 4-14. PREDICTED INJURIES AND FATALITIES FOR RADAR SYSTEM 3

	Impact Configuration						
AIS	FOF	FOS	Rollover	VVF	VVS	VVR	Total
0	5,795	230	3,114	34,097	34,793	5,839	8,5939
1	2,854	1,562	1,845	9,886	9,977	1,719	27,843
2	765	342	1,065	1,572	1,223	67	5,034
3	286	235	416	512	863	16	2328
4	47	67	54	96	149	8	421
5	28	27	37	25	56	1	174
6	45	74	188	75	189	9	580
Total	9,821	4,608	6,718	46,264	47,250	7,660	122,321

TABLE 4-15. PREDICTED INJURIES AND FATALITIES FOR RADAR SYSTEM 4

	Impact Configuration						
AIS	FOF	FOS	Rollover	VVF	VVS	VVR	Total
0	5,796	2,301	3,115	32,376	35,124	2,964	81,676
1	2,855	1,561	1,845	9,614	10,095	915	26,885
2	765	342	1,065	1,555	1,239	38	5,004
3	286	235	416	517	875	9	2,338
4	47	67	54	100	151	4	423
5	28	27	37	26	57	0	175
6	45	74	188	81	191	7	586
Total	9,821	4,607	6,719	44,270	47,733	3,938	117,088

TABLE 4-16. PREDICTED INJURIES AND FATALITIES FOR RADAR SYSTEM 5

	Impact Configuration						
AIS	FOF	FOS	Rollover	VVF	VVS	VVR	Total
0	5,795	2,299	3,114	32,163	35,127	2,964	81,462
1	2,854	1,560	1,845	9,497	10,096	915	26,767
2	765	342	1,065	1,525	1,240	38	4,975
3	286	235	416	500	875	9	2,321
4	47	67	54	95	151	4	418
5	28	27	37	25	57	0	174
6	45	74	188	75	191	7	580
Total	9,820	4,604	6,719	43,880	47,737	3,937	116,697

TABLE 4-17. VALUES OF XPIM USED IN THE KRAESP MODEL FOR SYSTEMS 2 THROUGH 5

Clock Direction	Mode	Probability of Impact by Clock Direction and Mode			
		System 2	System 3	System 4	System 5
11,12,1	VVF	0.12561	0.12625	0.12544	0.12475
	FOF	0.02808	0.02961	0.03075	0.03085
2-4, 8-10	VVS	0.06734	0.06423	0.06738	0.06761
	FOS	0.00715	0.00681	0.00707	0.00709
5-7	VVR	0.01123	0.01686	0.00900	0.00903
13	Rollover	0.05833	0.05557	0.05771	0.05790

TABLE 4-18. PREDICTED NON-MOTORIST INJURIES AND FATALITIES BY RADAR SYSTEM AND BY ACTUAL COUNT

Injury Level (AIS)	Actual Count	Baseline System	System 2	System 3	System 4	System 5
0	681	682	601	614	606	603
1	1,886	1,884	1,645	1,682	1,659	1,650
2	466	466	401	410	404	402
3	299	299	256	261	258	257
4	80	80	68	70	69	68
5	33	33	28	29	28	28
6*	158	163	121	122	121	120
Total	3,603	3,607	3,120	3,188	3,145	3,128

*AIS6 has been recoded to represent fatalities.

would be obtained. Table 4-19 presents the results for the predicted property damage by accident configuration for each radar system. Table 4-20 shows the absolute and relative benefit in terms of injuries and fatalities and property damage for the different radar systems relative to the baseline (see Figures 4-27 through 4-34.)

TABLE 4-19. PREDICTED AND ACTUAL PROPERTY DAMAGE LOSS BY RADAR SYSTEM (MILLIONS OF DOLLARS)

Accident Configuration	Actual Count	Baseline System	System 2	System 3	System 4	System 5
FOF	9.09	9.29	7.85	8.34	8.34	8.34
FOS	3.65	3.52	3.52	3.52	3.52	3.52
Rollover	6.58	6.79	6.79	6.79	6.79	6.79
VVF	23.42	22.74	18.83	19.38	19.23	18.94
VVS	18.45	18.77	17.70	17.99	18.19	18.19
VVR	2.54	2.35	1.16	1.67	0.96	0.96
Non-Motorist	1.10	1.05	0.90	0.91	0.90	0.90
Total	64.83	64.51	56.74	58.59	57.93	57.63
Accident Involvements	85,147	85,147	73,888	77,472	74,680	74,426
Mean Loss per Involvement ($)	761	758	768	756	776	774

TABLE 4-20. SUMMARY OF BENEFITS FOR RADAR SYSTEMS SHOWING THE NUMBER AND PERCENT OF INJURIES, ACCIDENTS AND PROPERTY DAMAGE AVOIDED

Radar System Two[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	710	11	1.4	16	367	12	151	17	58	17	9	16	7	20	10	18	602	14
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ROLL/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	6,270	19	3.9	17	2,042	18	310	17	105	18	93	19	7	23	23	24	2,509	18
VVS	1,122	4	1.1	6	363	4	40	3	30	3	5	3	2	3	6	3	446	4
VVR	2,664	53	1.2	51	1,380	56	65	60	29	67	7	58	2	100	19	76	1,493	56
Ped[4]	487	14	0.2	15	239	13	65	14	43	14	12	15	5	15	42	26	406	14
Total	11,253	7.8	13	12	4,392	14	632	11	256	9	54	10	23	10	100	13	5,457	13

[1]Defined by the control law $R_B = 2\dot{R}$.
[2]Includes accidents with AIS = 0 injuries.
[3]In millions of dollars.
[4]Tabulated for unmodified Vrel.

TABLE 4-20. (Cont'd)

Radar System Three[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	73	1	1.0	10	149	5	134	15	49	15	9	16	7	20	10	18	358	8
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roll/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	4,802	15	3.4	15	1,612	14	251	14	88	15	19	17	6	19	21	22	1,997	14
VVS	1,084	4	.8	4	356	3	40	3	29	3	5	3	2	3	6	3	438	3
VVR	1,291	26	.7	29	749	30	41	38	14	47	4	33	1	50	16	64	825	31
Ped[4]	419	12	.1	13	202	11	56	12	38	13	10	13	4	12	41	25	351	12
Total	7,669	9	5.9	9	3,032	9	523	9	218	8	47	9	20	9	94	12	3,934	9

[1]Defined by the control law $R_B = \dot{R}^2/2\mu g + \tau\dot{R}$.

[2]Includes accidents with AIS = 0 injuries.

[3]In millions of dollars.

[4]Tabulated for unmodified Vrel.

TABLE 4-20. (Cont'd)

Radar System Four[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	73	1	1.0	10	148	5	134	15	49	15	9	16	7	20	10	18	357	8
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roll/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	6,018	18	3.5	15	1,884	16	268	15	83	14	15	13	5	16	15	16	2,270	16
VVS	791	3	.6	3	238	2	24	2	17	2	3	2	1	2	4	2	287	2
VVR	3,117	62	1.4	59	1,553	63	70	65	21	70	8	67	2	100	18	72	1,672	63
Ped[4]	462	13	.1	14	225	12	62	13	41	14	11	14	5	15	42	26	386	13
Total	10,561	12	6.6	10	4,050	12	559	9	211	7	46	9	20	9	89	11	4,975	12

[1]Defined by the control law $R_B = V_1^2/2\mu g - V_2^2/2\mu g + \tau V_1$.
[2]Includes accidents with AIS = 0 injuries.
[3]In millions of dollars.
[4]Tabulated for unmodified Vrel.

TABLE 4-20. (Cont'd)

Radar System Five[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	73	1	1.0	10	149	5	134	15	49	15	9	16	7	20	10	18	358	8
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roll/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	6,255	19	3.8	17	2,001	17	298	16	100	17	20	17	6	19	21	22	2,496	17
VVS	791	3	.6	4	237	2	23	2	17	2	3	2	1	2	4	2	285	2
VVR	3,117	62	1.4	59	1,553	63	70	65	21	70	8	67	2	100	18	72	1,672	63
Ped[4]	479	13	.2	15	234	12	64	14	42	14	12	15	5	15	43	26	400	14
Total	10,715	13	6.9	11	4,177	13	590	10	229	8	52	10	21	9	96	12	5,165	12

[1]Defined by the control law $R_B = V_1^2/2\mu g \pm V_2^2/2\mu g + \tau V_1$ (+ for head-on; otherwise -).
[2]Includes accidents with AIS = 0 injuries.
[3]In millions of dollars.
[4]Tabulated for unmodified Vrel.

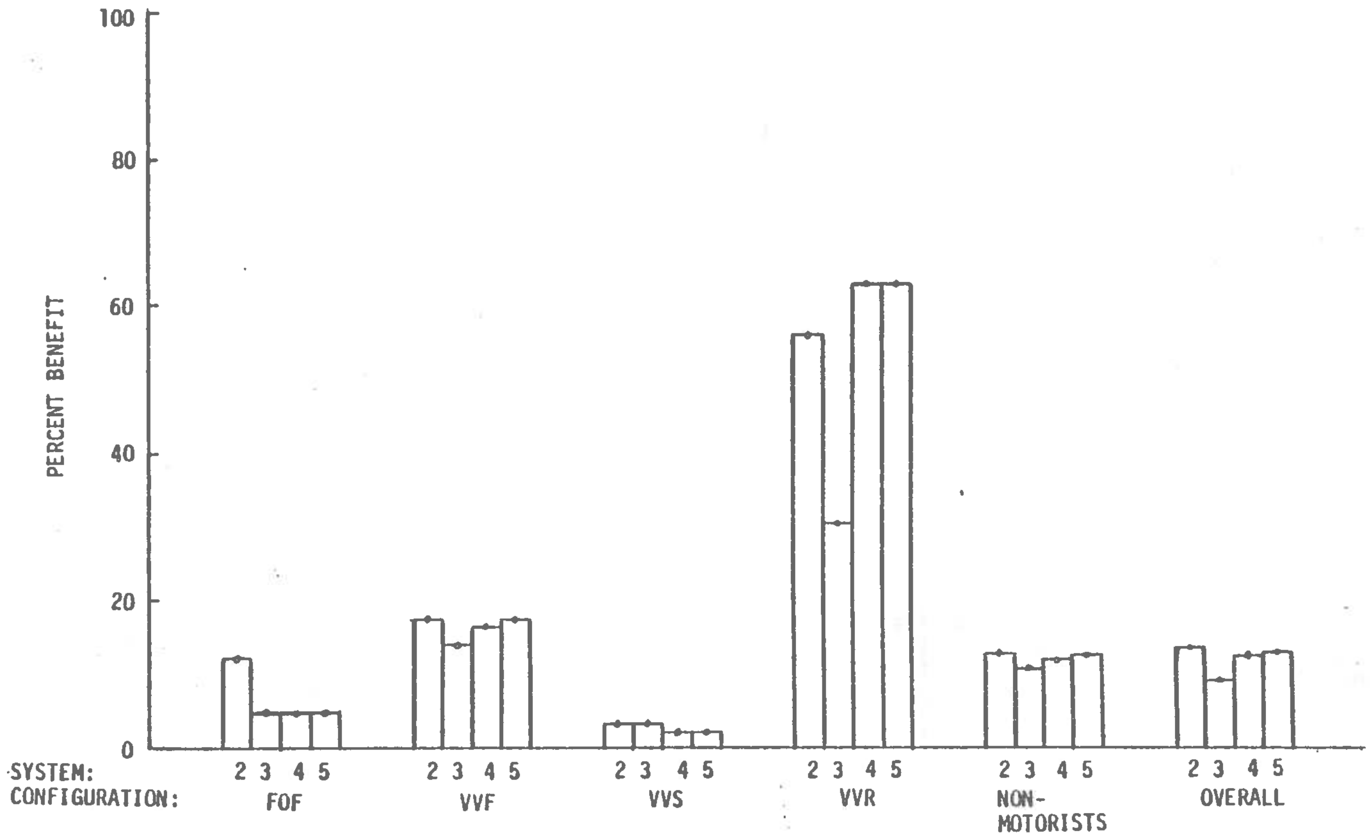


FIGURE 4-27. RELATIVE BENEFITS BY RADAR SYSTEM FOR AIS 1 INJURIES

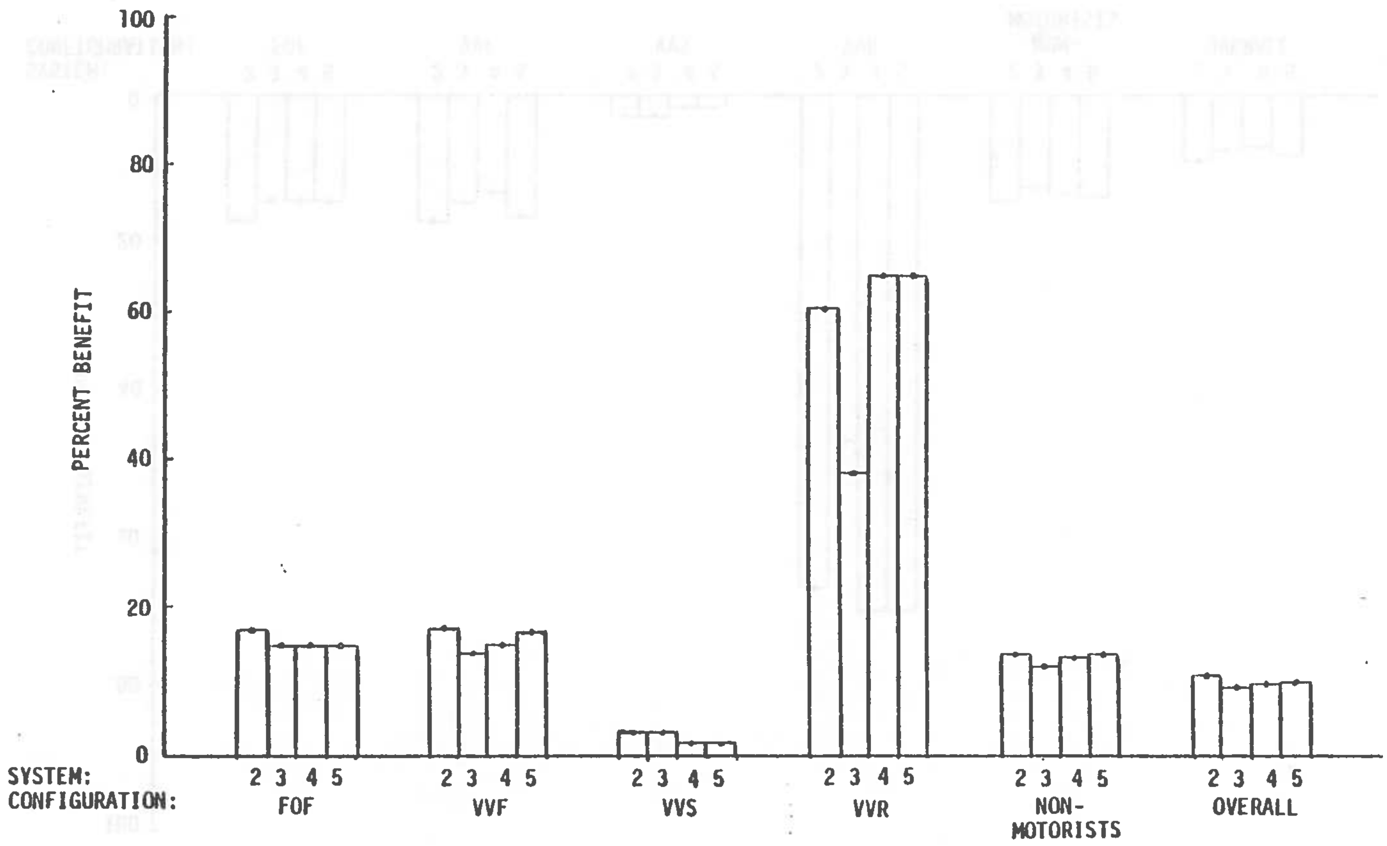


FIGURE 4-28. RELATIVE BENEFITS BY RADAR SYSTEM FOR AIS 2 INJURIES

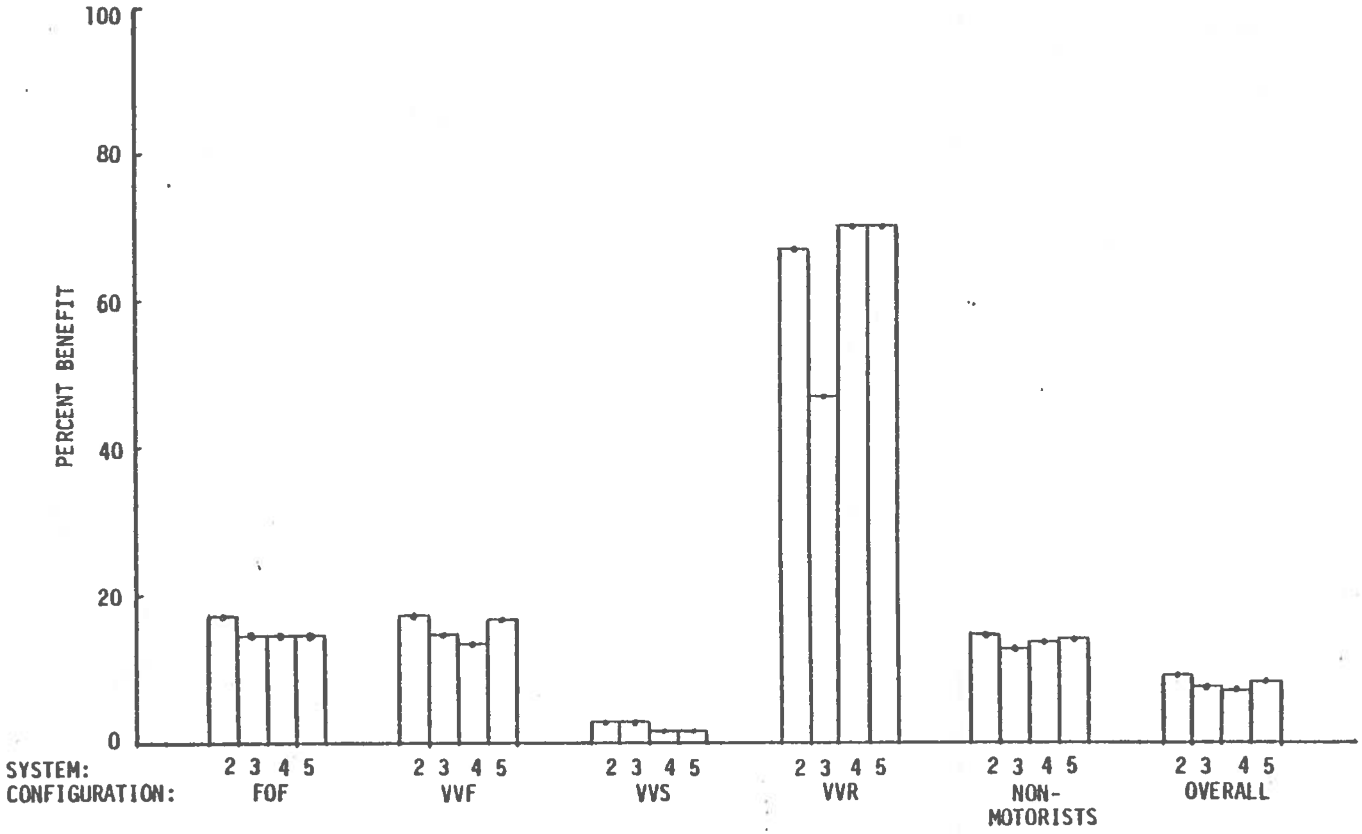


FIGURE 4-29. RELATIVE BENEFITS BY RADAR SYSTEM FOR AIS 3 INJURIES

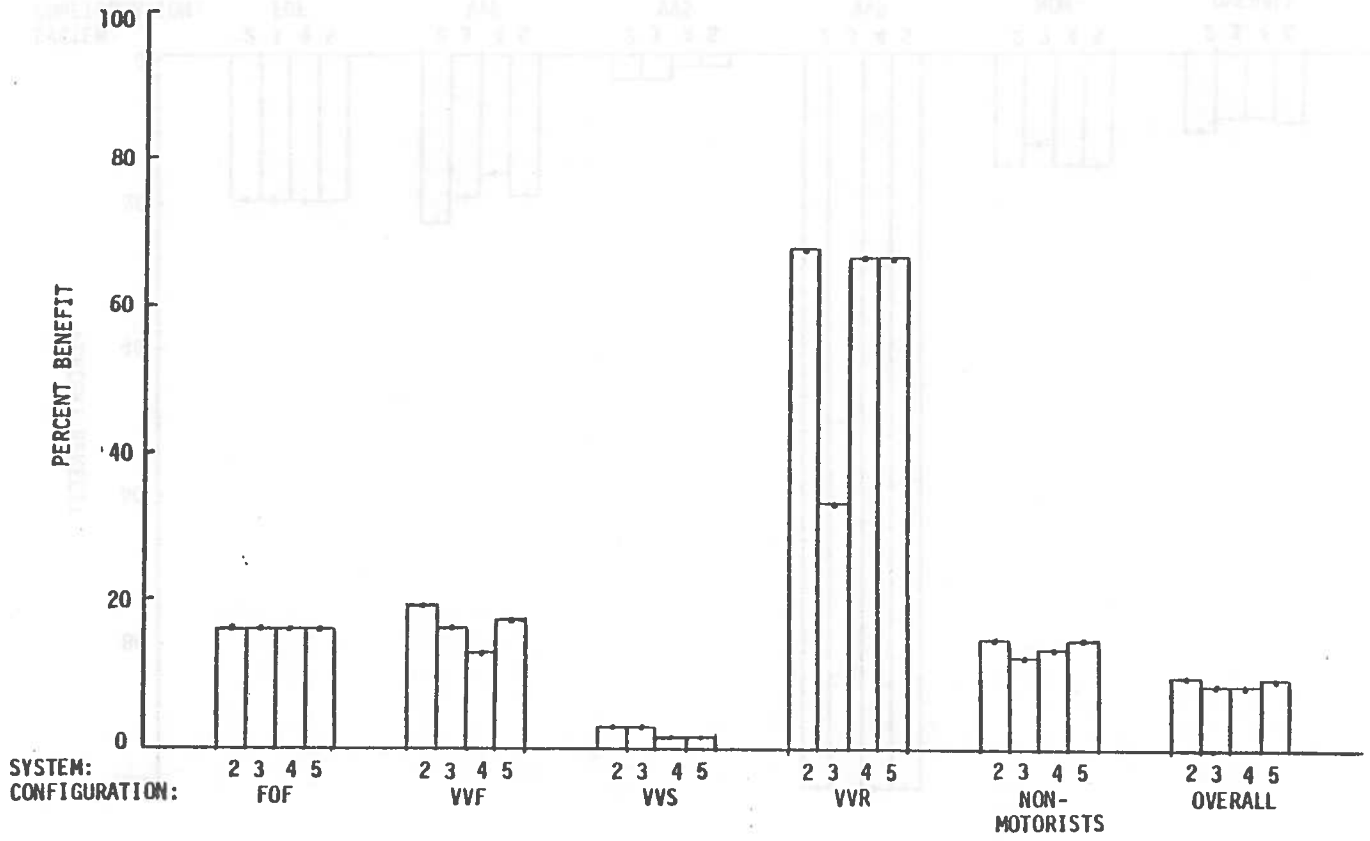


FIGURE 4-30. RELATIVE BENEFITS BY RADAR SYSTEM FOR AIS 4 INJURIES

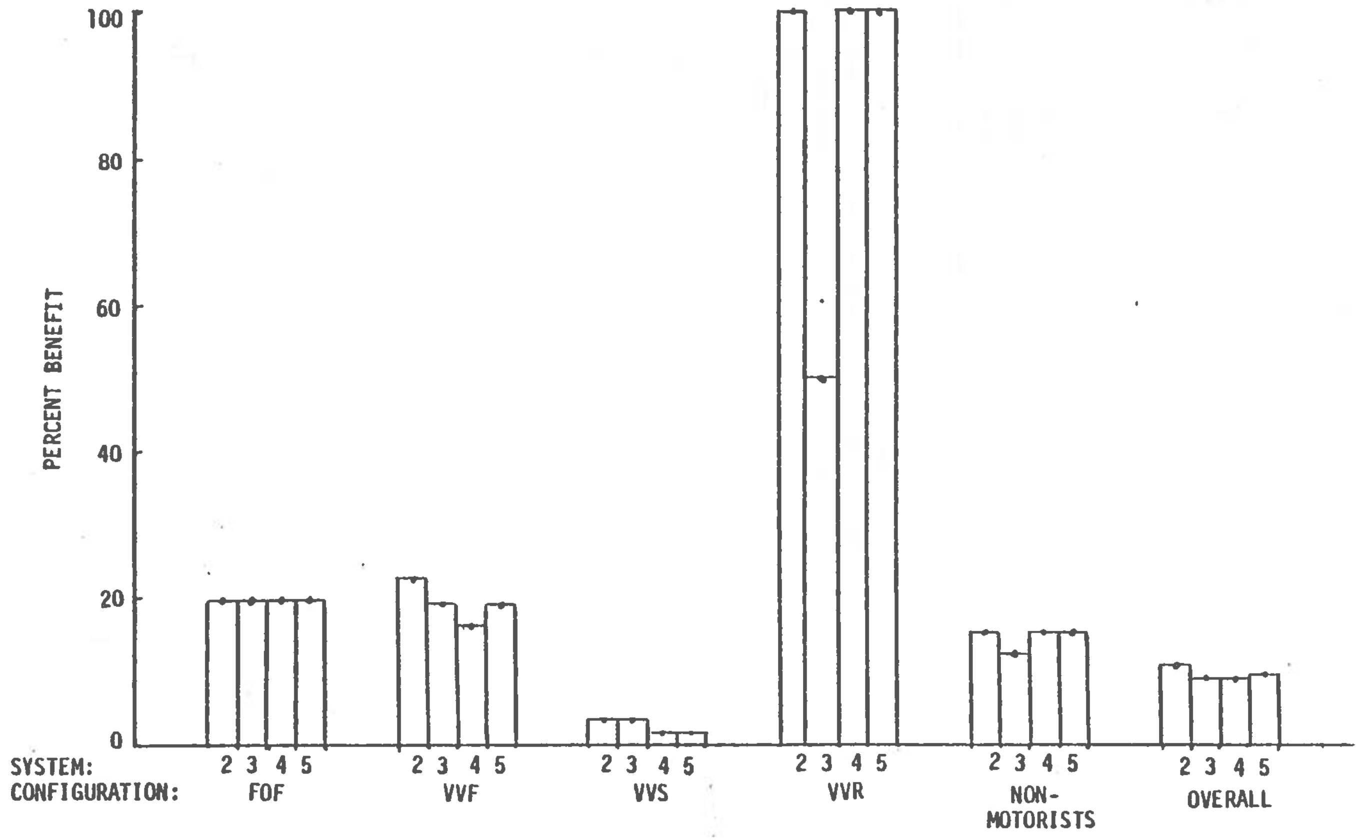


FIGURE 4-31. RELATIVE BENEFITS BY RADAR SYSTEM FOR AIS 5 INJURIES

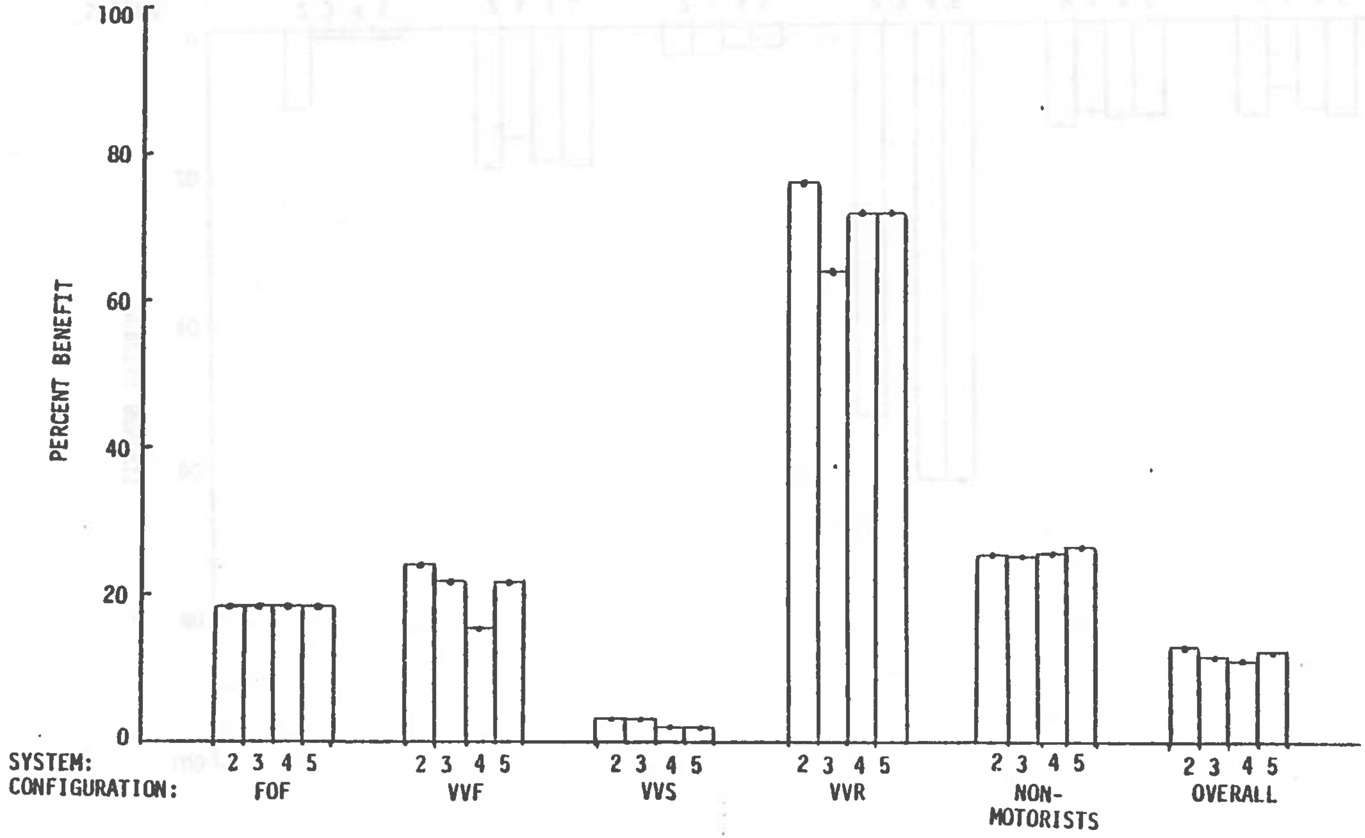


FIGURE 4-32. RELATIVE BENEFITS BY RADAR SYSTEM FOR FATALITIES

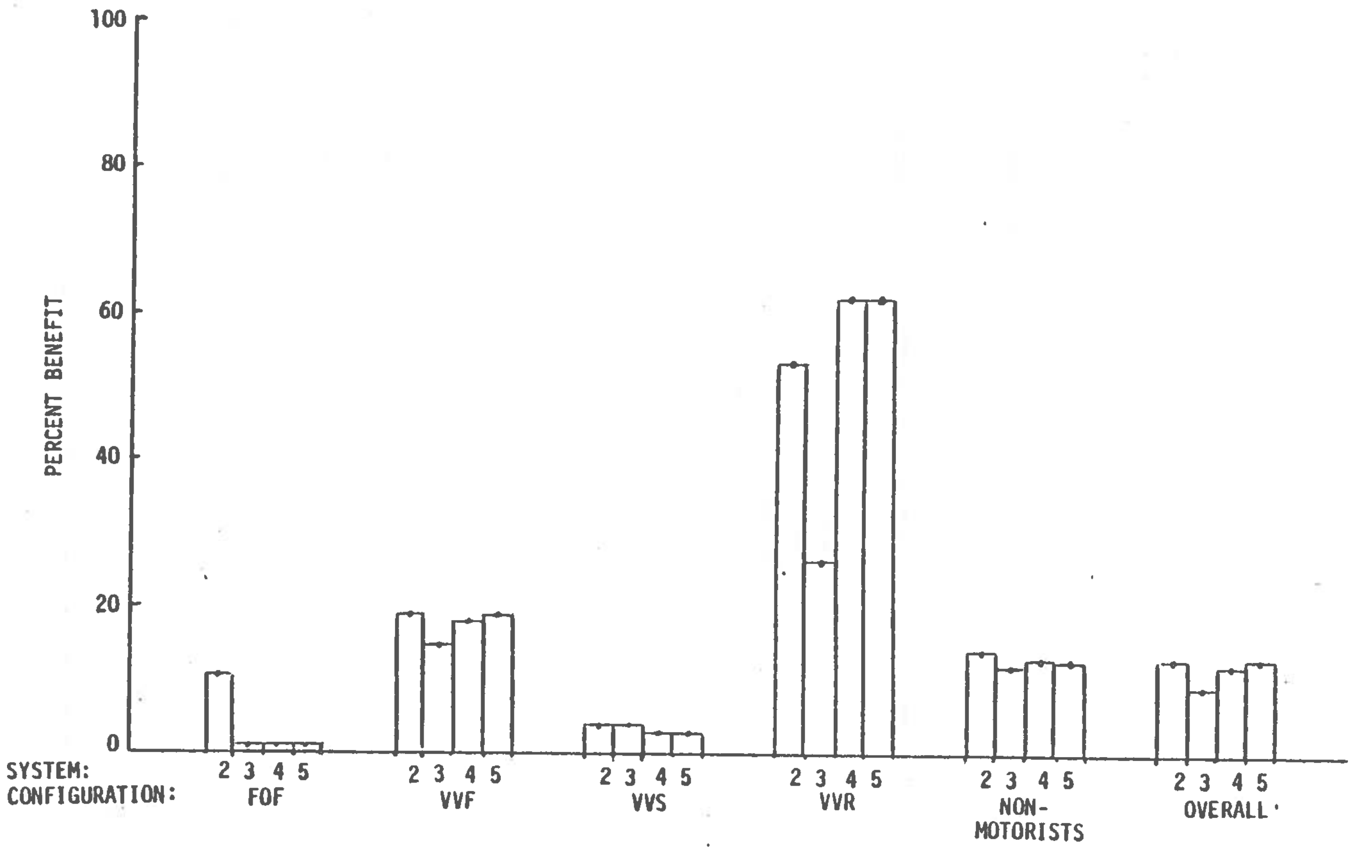


FIGURE 4-33. RELATIVE BENEFITS BY RADAR SYSTEM FOR ACCIDENTS

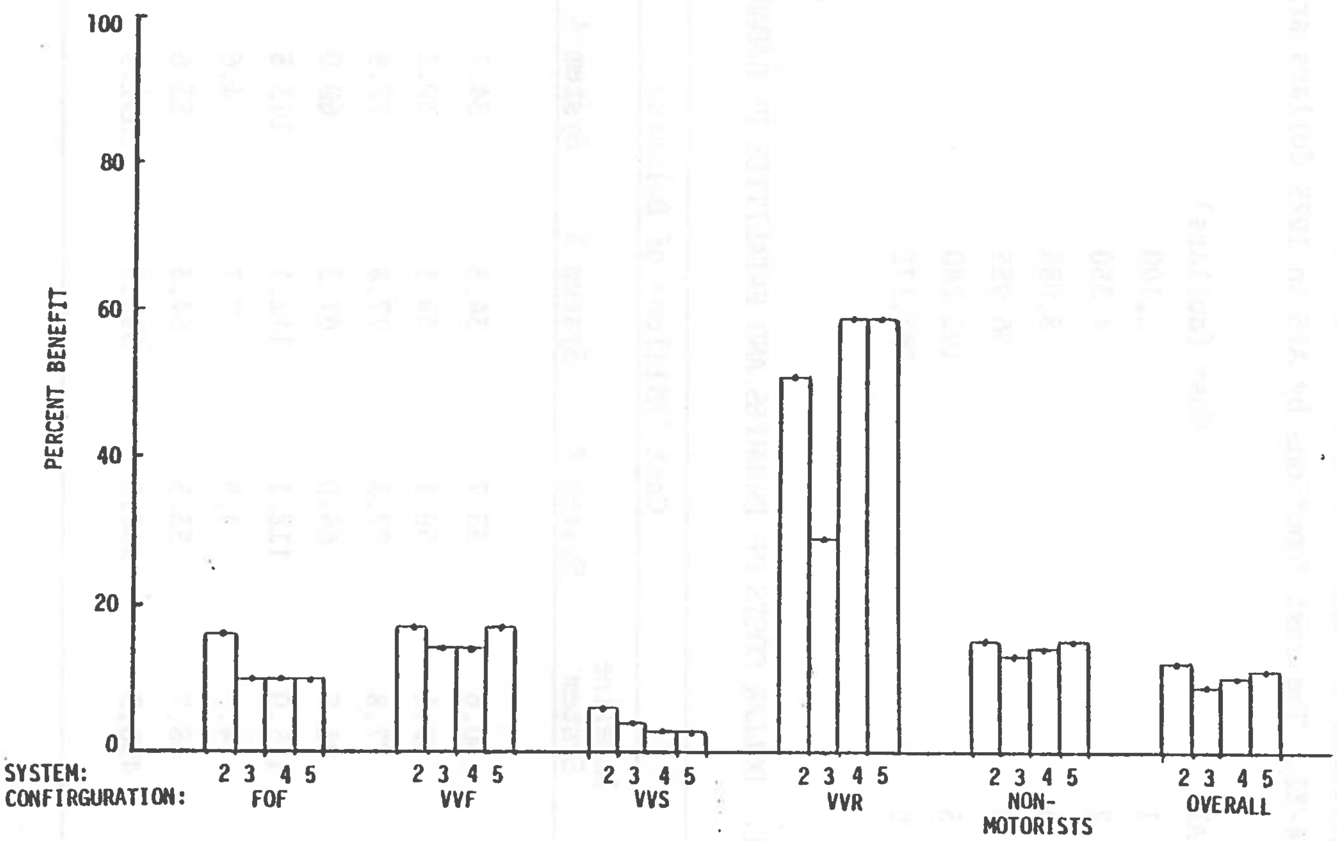


FIGURE 4-34. RELATIVE BENEFITS BY RADAR SYSTEM FOR PROPERTY DAMAGE

The injury and fatality losses shown in Tables 4-13 through 4-18 have been scaled and combined using a societal loss function obtained from Reference 24. The representative dollar costs of injuries and fatalities by radar system and accident configuration are shown in Table 4-21. Relative dollar benefits are shown in Table 4-22. The cost functions by AIS in 1975 dollars are:

AIS	Cost (dollars)
1	2,190
2	4,350
3	8,085
4	86,955
5	192,240
6	287,175

TABLE 4-21. DOLLAR COSTS OF INJURIES AND FATALITIES BY RADAR SYSTEM

Accident Configuration	Cost (Millions of Dollars)				
	Baseline System	System 2	System 3	System 4	System 5
FOF	40.6	33.7	34.3	34.3	34.3
FOS	39.1	39.1	39.1	39.1	39.1
Rollover	77.8	77.8	77.8	77.8	77.8
VVF	81.5	65.0	67.3	69.0	66.1
VVS	115.9	112.1	112.1	113.5	113.5
VVR	14.7	4.8	7.7	4.6	4.6
Non-Motorist	68.7	53.5	54.3	53.6	53.2
Total	438.3	386.0	392.7	391.9	388.6

TABLE 4-22. RELATIVE DOLLAR COST BENEFIT FOR INJURIES AND FATALITIES BY RADAR SYSTEM

Accident Configuration	Percent Benefit			
	System 2	System 3	System 4	System 5
FOF	17	16	16	16
FOS	0	0	0	0
Rollover	0	0	0	0
VVF	20	17	15	19
VVS	3	3	2	2
VVR	67	48	69	69
Non-Motorist	22	21	22	23
Total	12	10	11	11

These costs have been inflated to 1979 dollars by a factor of 1.330, which is the ratio of the respective Consumer Price Indexes in 1979 and 1975.

The total costs in 1979 may be distributed over the North Carolina vehicle population to obtain per vehicle dollar losses due to injury and property damage. Reference 24 estimates a total of 3,331,891 automobiles registered in North Carolina in 1979. Applying this figure to Table 4-21 and scaling the costs by the fraction of all North Carolina accidents which are represented in the analysis, one obtains Table 4-23, which shows the annual dollar loss per registered vehicle. Of 208,143 weighted automobile involvements in North Carolina in 1979, 84,937 are considered as known configuration and known Vrel. Therefore, the dollar losses in Table 4-21 should be multiplied by 208,143 ÷ 84,937 to represent all North Carolina automobile accidents. Table 4-24 expresses the absolute and relative per automobile benefits of radar braking. Using the life cycle system cost estimate of $45 per year for an automatic anti-skid braking system one can compute the net benefit per vehicle for such systems. Similarly, using $27 per vehicle, one can compute the warning-

TABLE 4-23. PER AUTOMOBILE DOLLAR COSTS OF PROPERTY DAMAGE, INJURIES AND FATALITIES BY RADAR SYSTEM FOR ADJUSTED NORTH CAROLINA ACCIDENTS IN 1979

Accident Configuration	Baseline System	System 2	System 3	System 4	System 5
FOF	37	31	31	31	31
FOS	31	31	31	31	31
Rollover	62	62	62	62	62
VVF	77	62	64	65	63
VVS	99	95	96	97	97
VVR	13	4	7	4	4
Non-Motorist	51	40	41	40	40
Total	370	326	332	331	328

TABLE 4-24. PER AUTOMOBILE DOLLAR BENEFIT FOR PROPERTY DAMAGE, INJURIES, AND FATALITIES BY RADAR SYSTEM FOR ADJUSTED* NORTH CAROLINA ACCIDENTS IN 1979

Accident Configuration	System 2		System 3		System 4		System 5	
	$	%	$	%	$	%	$	%
FOF	6	16	6	16	6	16	6	16
FOS	0	0	0	0	0	0	0	0
Rollover	0	0	0	0	0	0	0	0
VVF	15	19	13	17	12	16	14	18
VVS	4	4	3	3	2	2	2	2
VVR	9	69	6	46	9	69	9	69
Non-Motorist	11	22	10	20	11	22	11	22
Total	45	12	38	10	40	11	42	11
Life Cycle Cost	45		45		45		45	
Benefit	0		-7		-5		-3	

*Adjusted by speed limits to represent national experience.

only net benefit. Costs for the warning-only system have been computed using Tdel = 1.0 second. These results are entered in Table 4-25.

The relative cost-benefit performance of the different radar systems is illustrated in Figure 4-35.

The cost estimates used for the radar systems are based on a moderate level of production quantities, 50 percent life cycle maintenance cost, and a useful life of 10 years. The cost estimates on that basis are as shown below:

	Production Cost	Ten Year Life Cycle Cost
Warning only system	$177	$26.55/year
Automatic Anti-skid braking	$302	$45.30/year

In larger production quantities, the system cost may be considerably reduced.

The Radar Brake Algorithm represents the properties of the different radar systems by the respective control laws together with certain parameters such as the beamwidth, the range cutoff, etc. These parameters are summarized in Table 4-26 where the control laws are reviewed and possible alternative values of each parameter are indicated. The effects of selecting alternative values of the different parameters may be examined by tabulating the property damage losses in each of the accident configurations for each of the systems. Tables 4-27 and 4-28 present this material for a subset of the 1979 North Carolina data consisting of every 20th accident in the full file.

4.5 TRADE-OFF BETWEEN FALSE ALARMS AND MISSED TARGETS

An important consideration when analyzing feasibility and benefit potential of the radar brake systems is the question of false alarms and missed targets. A major requirement from the radar braking system will be that the system should not interfere with normal, acceptable driving habits. In most vehicle braking events, no accident is about to occur and the driver's normal braking should not

TABLE 4-25. SUMMARY OF COST BENEFIT PERFORMANCE OF RADAR SYSTEMS IN 1979 DOLLARS

	System 2	System 3	System 4	System 5
<u>All Automatic Braking System</u>				
Total Per Vehicle Benefit				
Non-motorists excluded	34	28	29	31
Non-motorists included	45	38	40	42
Per Vehicle Per Year Life Cycle Cost	45	45	45	45
Per Vehicle Net Benefit (Loss)				
Non-motorists excluded	(11)	(17)	(16)	(14)
Non-motorists included	0	(7)	(5)	(3)
<u>Warning-Only Radar System</u> (0.4 second delay)				
Total Per Vehicle Benefit				
Non-motorists excluded	28	17	26	27
Non-motorists included	29	21	27	28
Per Vehicle Per Year Life Cycle Cost	27	27	27	27
Net Benefit (Loss)				
Excluded	1	(10)	(1)	0
Included	2	(6)	0	1

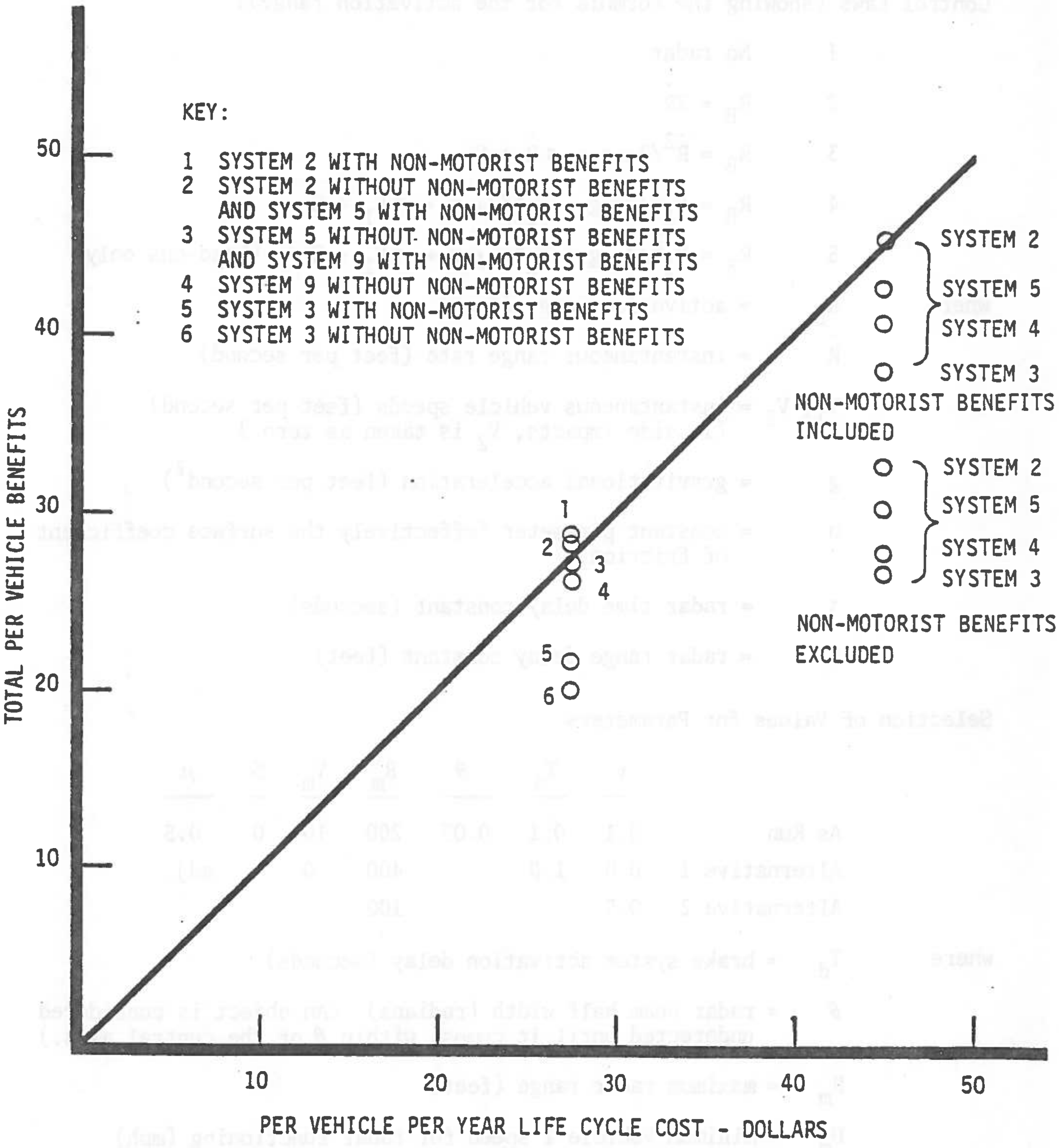


FIGURE 4-35. COST EFFECTIVENESS COMPARISON FOR FOUR RADAR SYSTEMS

TABLE 4-26. REVIEW OF THE RADAR SYSTEM CONTROL LAWS AND PARAMETERS

Control Laws (showing the formula for the activation range):

1	No radar
2	$R_B = 2\dot{R}$
3	$R_B = \dot{R}^2/2\mu g + \tau\dot{R} + S$
4	$R_B = V_1^2/2\mu g - V_2^2/2\mu g + \tau V_1 + S$
5	$R_B = V_1^2/2\mu g + V_2^2/2\mu g + \tau V_1 + S$ (head-ons only)

where

R_B = activation range (feet)

$\dot{R}$ = instantaneous range rate (feet per second)

V_1, V_2 = instantaneous vehicle speeds (feet per second) (In side impacts, V_2 is taken as zero.)

g = gravitational acceleration (feet per second^2)

u = constant parameter (effectively the surface coefficient of friction)

τ = radar time delay constant (seconds)

S = radar range delay constant (feet)

Selection of Values for Parameters

	τ	T_d	θ	R_m	V_m	S	μ
As Run	0.1	0.1	0.05	200	10	0	0.5
Alternative 1	0.0	1.0		400	0		adj.
Alternative 2	0.5			100			

where

T_d = brake system activation delay (seconds)

θ = radar beam half width (radians) (An object is considered undetected until it comes within θ of the central axis.)

R_m = maximum radar range (feet)

U_m = minimum Vehicle 1 speed for radar functioning (mph)

adj. = parameter u is adjusted to different values depending on the surface type.

TABLE 4-27. PROPERTY DAMAGE LOSSES FOR BASELINE PARAMETERS FOR A SUBSET OF THE DATA (IN THOUSANDS OF DOLLARS)

Accident Configuration	System 1	System 2	System 3	System 4	System 5
FOF	202	149	147	147	147
FOS	83	83	83	83	83
Rollover	181	181	181	181	181
VVF	538	450	461	458	454
VVS	475	458	460	465	465
VVR	53	25	38	21	21
Non-Motorist	26	21	21	21	21

TABLE 4-28. SUMMARY OF PROPERTY DAMAGE LOSS CHANGES AS A FUNCTION OF VARIATION IN RADAR SYSTEM PARAMETERS

	System 3	System 4	System 5
1. τ changed from 0.1 second to 0.0 second			
FOF	+2.7%	+2.7%	+2.7%
VVF	+1.7	+0.7	+0.9
VVR	+5.2	±0.0	±0.0
No Radar	+0.5	+0.2	+0.2
Rear-End	+20.0	±0.0	±0.0
Head-On	±0.0	±0.0	±0.0
Fixed Object	+100.0	+100.0	+100.0
Right-to-Left Crossing	+2.0	+1.0	+1.0
Left-to-Right Crossing	±0.0	±0.0	±0.0
2. τ changed from 0.1 second to 0.5 second			
VVF	-1.0%	-0.9%	-0.9%
VVS	-.2	-1.1	-1.1
VVR	-7.9	+9.5	+9.5
No Radar	-0.2	-0.2	-0.2
Rear-End	-20.0	+100.0	+100.0
Head-On	±0.0	±0.0	-12.5
Fixed Object	-14.0	-14.0	-14.0
Right-to-Left Crossing	±0.0	-2.9	-2.9
Left-to-Right Crossing	±0.0	-1.4	-1.4

TABLE 4-28 (continued)

	System 2	System 3	System 4	System 5
3. T_d changed from 0.1 second to 1.0 second				
FOF	+15.4%	+27.9%	+27.9%	+27.9%
VVF	+10.4	+13.2	+11.4	+12.1
VVS	+3.2	+3.0	+1.9	+1.9
VVR	+56.0	+28.9	+61.9	+61.9
Non-Motorists	+9.5	+19.0	+9.5	+9.5
No Radar	+3.0	+3.2	+2.8	+2.3
Rear-End	+375.0	+106.7	+1,400.0	+1,400.0
Head-On	+28.6	+14.3	+11.1	+12.5
Fixed Object	+400.0	+985.7	+985.7	+985.7
Right-to-Left Crossing	+12.9	+13.9	+9.5	+9.5
Left-to-Right Crossing	+4.5	+4.5	+1.4	+1.4
4. R_{max} changed from 200 feet to 400 feet				
VVF	-1.3%	-1.7%	±0.0	-1.5%
No Radar	-0.2	-0.3	±0.0	-0.3
Rear-End	±0.0	±0.0	±0.0	±0.0
Head-On	-57.1	-71.4	±0.0	-62.5
Fixed Object	±0.0	-42.9	-42.9	-42.9
Right-to-Left Crossing	±0.0	±0.0	±0.0	±0.0
Left-to-Right Crossing	±0.0	±0.0	±0.0	±0.0

TABLE 4-28 (continued)

	System 2	System 3	System 4	System 5
5. R_{max} changed from 200 feet to 100 feet				
FOF	+8.7%	+10.2%	+10.2%	+10.2%
VVF	+1.7	+2.0	+1.1	+2.0
VVS	+0.2	±0.0	+0.2	+0.2
VVR	+4.0	+2.6	+4.8	+4.8
Non-Motorists	±0.0	+4.8	+4.8	+4.8
No Radar	+0.4	+0.4	+0.3	+0.5
Rear-End	+50.0	+13.3	+200.0	+200.0
Head-On	+28.6	+28.6	±0.0	+12.5
Fixed Object	+166.7	+242.9	+242.9	+242.9
Right-to-Left Crossing	+0.0	+1.0	+1.0	+1.0
Left-to-Right Crossing	+0.0	+0.0	+0.0	+0.0
6. μ changed from 0.5 to adjustable				
FOF	+0.0%	-0.7%	-0.7%	-0.7%
VVF	+0.2	-0.2	-0.7	-0.4
VVS	-0.4	-1.5	-0.4	+0.0
VVR	+0.0	-2.6	+0.0	+0.0
No Radar	+0.3	+0.2	+0.0	+0.2
Rear-End	+0.0	-6.7	+0.0	+0.0
Head-On	-28.6	-28.6	-22.2	-37.5
Fixed Object	+0.0	-42.8	-42.8	-42.8
Right-to-Left Crossing	+0.0	+0.0	-1.0	-1.0
Left-to-Right Crossing	+0.0	+0.0	+0.0	+0.0

TABLE 4-28 (continued)

	System 2	System 3	System 4	System 5
7. V_{min} changed from 10 mph to 0 mph				
VVF	-1.1%	-0.9%	±0.0%	±0.0%
VVS	-1.3	-1.3	±0.0	±0.0
No Radar	-0.5	-0.4	-0.1	±0.0
Rear-End	±0.0	±0.0	±0.0	±0.0
Head-On	±0.0	±0.0	±0.0	±0.0
Fixed Object	±0.0	±0.0	±0.0	±0.0
Right-to-Left Crossing	±0.0	±0.0	±0.0	±0.0
Left-to-Right Crossing	-3.0	-3.0	±0.0	+0.0

be taken over or dictated by the radar braking system. Such over-control will create an unacceptable over-dependence on the part of the driver on the radar system and is not deemed appropriate.

False alarms will annoy a driver. The consequences of a false alarm will be much greater when automatic braking takes place than when "Warning Only" is given. If the false alarm braking is sudden and hard, there is a possiblity that the radar-equipped vehicle will be rear-ended by a following vehicle or will skid into an accident. The following car may also be equipped with a radar system and may stop. However, gradual introduction of radar systems is a more possible scenario.

It is possible that in an environment where false alarms are possible, a driver is likely to turn off the radar braking system or use the "Warning Only" mode, thus reducing the ability to prevent those accidents where little or no warning time is available.

Types of false alarms were discussed earlier in Section 3.3. Also discussed there were methods that can be used to reduce the number of false alarms. The analysis of the existing radar brake systems showed that the systems can be classified under three levels based on the sophistication of the signal processing technique. The signal processing sophistication and the control logic used influence the possibility of false alarms and the missed targets. Among the three levels of sophistication, the Level I system is the least sophisticated and the Level III systems will be the most sophisticated. The Level I system, of which Bendix's system is a typical example, will show the greatest possiblity of false alarms. The Level II systems, of which the German and Japanese systems and RCA are typical examples, will show a rate of false alarms much lower than the Level I system, but they will be inferior to Level III systems. The Level III systems are not yet out on the vehicles, but are under development and likely to reach the test prototype stage in the next few years. The control laws of the Level III systems will employ a "gating technique" or similar other arrangements to further reduce the possibility of false alarms and missed targets.

The benefit analysis presented in Section 4.4 did not take into account the consequences of false alarms and missed targets. The consequences of false alarms are very difficult to quantify. In general, it can be said that some false alarms can result in accidents. However, it is difficult to quantify what percentage of false alarms will result in accidents. Next, it is difficult to describe the type of accident that will occur and what will be the corresponding property damage and injury consequences. In general, it can be said that as a result of false alarm triggered braking, the likelihood of rear-end collisions will increase. If the braking is hard, it can also lead to skidding unless an anti-skid system is made part of the radar brake system.

For radar systems to be feasible, practical and acceptable, the frequency of false alarms and missed targets must approach zero.

4.6 ANTI-SKID SYSTEMS

Amongst the radar braking systems evaluated, Bendix, RCA, Nissan, and reportedly Rashid (no data were available on the Rashid system), have automatic braking as a part of the overall radar braking system. The Bendix system, the RCA system for the RSV, and the Nissan system use an anti-skid feature as part of the braking system. The German developers tend to favor "warning only" systems.

All anti-skid systems work on the principle of coming into action only when an imminent wheel lock-up is sensed. The wheel lock-up tendency can be created by very hard braking for the available tire-ground friction. When an imminent wheel lock-up is sensed, the anti-skid system modulates the brake line pressure using a feedback control loop that can take into account vehicle speed and deceleration, wheel rotational speed and deceleration, coefficient of friction, and selected pre-established reference values.

In the early seventies, some luxury U.S. automobiles were offered with anti-skid braking systems as options. Those anti-skid systems were for the rear axle only.

Work done by Bendix, Teldix, Bosch, and Teves has shown that the main advantage of the anti-skid systems is shown under low coefficient tire-road conditions.

Hence, for a dry road surface with a skid number of about 70, the stopping distance with and without an anti-skid system is likely to be about the same. As a matter of fact, a good driver can beat the anti-skid system. However, on low coefficient surfaces like icy roads the stopping distance performance can be shortened by as much as 50 to 70 percent.

The other important feature of the anti-skid systems is to retain lateral stability of the vehicle and steering control by preventing wheel lock-up and attendant loss of road cohesion. A Bendix report (Ref. 22) published in 1973 analytically evaluated the cornering performance of a full-size passenger car, with and without anti-skid systems. The anti-skid systems the report analyzed included two-wheel and four-wheel anti-skid systems. Here, we are going to concentrate on four-wheel anti-skid system performance.

The vehicle was supposed to lose control when the front wheel developed excessive slip, resulting in the loss of tire lateral force. The resulting motion can be straight ahead; however, the steering control is lost. The loss of vehicle stability was assumed to occur when the rear wheels had excessive slip. This resulted in loss of lateral force and the rear end breakaway.

The vehicle control and stability were measured by dynamic variables such as lateral acceleration, path curvature, yaw gain, and vehicle slip angle. The loss of stability is indicated by a rapid increase in these variables and the loss of control is indicated by a rapid decrease in the dynamic variables.

The results showed that the four-wheel anti-skid system was capable of eliminating the loss of stability and control under selected test maneuvers, and increased the vehicle's capability substantially under limited lateral performance (lateral acceleration of 0.6 to 0.8 G).

In order to estimate the possible benefits of anti-skid brake systems over and above the benefits of automatic radar braking, several runs were made on a subset of the 1979 North Carolina data. This subset contained every twentieth accident from the original file and resulted in 12,402 cases analyzed. Variable MUINC is used in the Radar Brake Algorithm to increase the effective coefficient of friction if automatic braking is activated. This is intended to reflect the greater stopping power available with an anti-skid system. For this investigation, property damage losses for each of the radar systems in the different KRAESP accident configurations (KSPTYP) and in the different BRAKE configurations (CONFIG) were tabulated for values of MUINC of 0.0, 0.1, and 0.2. From these tables were computed the relative benefit for MUINC - 0.1 and 0.2, compared to MUINC = 0.0 (no anti-skid). The benefit is the relative decrease in property damage with MUINC = 0.2 or 0.2 from the result for a given radar system with MUINC = 0.0. These results are presented in Table 4-29. It can be seen that anti-skid braking can significantly enhance the performance of the radar brake system, at least in certain modes. The radar is reminded that in cases where CONFIG is not NULL, a radar system has been called into operation. The results by the various KRAESP configurations are diluted by a large number of cases where radar is not involved, thus also not involving the anti-skid feature.

4.7 COST-SHARING OF RADAR SYSTEMS

In general, the 1981 automobile has electronic components worth about $250 on an average. It is expected that the amount will rise to about $1,000 by the end of the 1980s (Ref. 23). The new electronic hardware that is being added in increasing volume includes:

- Electronic ignition systems;
- Vehicle system status display;
- Diagnostics systems; and
- Cruise control.

Some of these systems can feasibly share components and controls with radar brake systems, thereby reducing the total cost of the package.

Cruise control, for example, requires input of vehicle speed for its feedback control loop. Additionally, the cruise control has a brake application override of the cruise control function. Both these inputs will be required by the radar system also and can be shared by both systems.

TABLE 4-29. RELATIVE PROPERTY DAMAGE BENEFIT OF ANTI-SKID BRAKING FOR THE DIFFERENT RADAR SYSTEMS

Configuration	System 2	System 3	System 4	System 5
		MUINC = 0.1		
KSPTYP:				
FOF	5	4	4	4
FOS	0	0	0	0
FOR	0	0	0	0
VVF	3	3	2	2
VVS	1	0	0	0
VVR	24	7	6	6
PED	2	2	0	0
UNK	1	3	3	3
TOT	2	2	1	2
CONFIG:				
Rear-End	65	18	40	40
Head-On	19	19	0	19
Fixed Object	27	24	23	23
R-L Crossing	2	2	1	1
L-R Crossing	1	1	1	1
NULL	1	1	0	0
		MUINC = 0.2		
KSPTYP:				
FOF	12	18	18	18
FOS	0	0	0	0
FOR	0	0	0	0
VVF	5	5	3	4
VVS	1	1	1	1
VVR	31	10	6	6
PED	2	2	2	2
UNK	2	5	5	5
TOT	4	5	4	4
CONFIG:				
Rear-End	83	26	60	60
Head-On	33	33	0	34
Fixed Object	60	77	77	77
R-L Crossing	4	4	3	3
L-R Crossing	2	2	1	1
NULL	1	1	1	1

Rapid advances in microprocessor technology in the last few years have resulted in a situation wherein a number of electronic functions in current and future automobiles can be integrated into one or more control units. Such a consolidation will substantially reduce the cost of an overall package and provide a number of additional functions that were not feasible economically, thus far.

There is also the possibility of using radar as a pre-impact sensor for passenger restraint systems. The current airbag restraints or pretension arrangements for seatbelts use impact sensors that are triggered by an accidental impact. A radar sensor can decide when an accident is unavoidable and trigger the airbag or belt-tensioning device, even before the actual impact takes place. This can add seconds to the time that is currently available for the airbag inflation and belt pretensioning techniques.

The current airbag techniques are based on availablity of a few milliseconds to inflate an airbag. If additional time is made available, a completely new type of information technique will have to be considered.

4.8 FUTURE BENEFITS

The KRAESP Model is designed to predict future injuries and fatalities by accident configuration to the year 1990. This projection takes into account anticipated changes in vehicle weights and sales by size class. Tables 4-30 through 4-36 present the anticipated injuries and fatalities by accident configuration for the four radar systems and the baseline system. Also given in these tables are the relative benefits of the different radar systems. Table 4-37 shows the results of scaling and summing these losses in dollar terms, together with the dollar benefit. All calculations are for 1990 projections in 1979 dollars, just as in Section 4.4.2, except that pedestrian (non-motorist) injuries are not included. The KRAESP Model was not used to project non-motorist injuries or property damage losses.

The total number of injuries and the dollar losses are increased in 1990 over 1979 due to the increased number of vehicles anticipated to be on the road. The

TABLE 4-30. NUMBER OF INJURIES AND FATALITIES AND PERCENT BENEFIT IN THE YEAR 1990 BY RADAR SYSTEM - FIXED OBJECT FRONT

		Number of Injuries and Percent Benefit							
	Baseline	System 2		System 3		System 4		System 5	
AIS	System	No.	%	No.	%	No.	%	No.	%
1	3,601	3,161	12	3,423	5	3,423	5	3,423	5
2	1,080	898	17	919	15	919	15	919	15
3	401	332	17	343	15	343	15	343	15
4	67	56	16	56	16	56	16	56	16
5	41	34	17	34	17	34	17	34	17
6*	66	54	18	54	18	54	18	54	18
Total	5,256	4,535	14	4,829	8	4,829	8	4,829	8

*AIS 6 recoded to represent fatalities.

TABLE 4-31. NUMBER OF INJURIES AND FATALITIES AND PERCENT BENEFIT IN THE YEAR 1990 BY RADAR SYSTEM - FIXED OBJECT SIDE

		Number of Injuries and Percent Benefit							
	Baseline	System 2		System 3		System 4		System 5	
AIS	System	No.	%	No.	%	No.	%	No.	%
1	1,871	1,871	0	1,871	0	1,871	0	1,871	0
2	410	410	0	410	0	410	0	410	0
3	281	281	0	218	0	281	0	281	0
4	81	81	0	81	0	81	0	81	0
5	32	32	0	32	0	32	0	32	0
6*	89	89	0	89	0	89	0	89	0
Total	2,764	2,764	0	2,764	0	2,764	0	2,764	0

*AIS 6 recoded to represent fatalities.

TABLE 4-32. NUMBER OF INJURIES AND FATALITIES AND PERCENT BENEFIT IN THE YEAR 1990 BY RADAR SYSTEM - ROLLOVER/NON-COLLISION

		Number of Injuries and Percent Benefit							
		System 2		System 3		System 4		System 5	
AIS	Baseline System	No.	%	No.	%	No.	%	No.	%
1	2,214	2,214	0	2,214	0	2,214	0	2,214	0
2	1,278	1,278	0	1,278	0	1,278	0	1,278	0
3	499	499	0	499	0	499	0	499	0
4	65	65	0	65	0	65	0	65	0
5	44	44	0	44	0	44	0	44	0
6*	226	226	0	226	0	226	0	226	0
Total	4,326	4,326	0	4,326	0	4,326	0	4,326	0

*AIS 6 recoded to represent fatalities.

TABLE 4-33. NUMBER OF INJURIES AND FATALITIES AND PERCENT BENEFIT IN THE YEAR 1990 BY RADAR SYSTEM - VEHICLE-TO-VEHICLE FRONT

		Number of Injuries and Percent Benefit							
		System 2		System 3		System 4		System 5	
AIS	Baseline System	No.	%	No.	%	No.	%	No.	%
1	13,870	11,406	18	11,925	14	11,598	16	11,456	17
2	2,218	1,841	17	1,912	14	1,891	15	1,856	16
3	738	608	18	629	15	625	14	614	17
4	143	117	18	120	16	125	13	119	17
5	38	30	21	31	18	33	13	31	18
6*	123	93	24	96	22	103	16	95	23
Total	17,130	14,095	18	14,713	14	14,385	16	14,171	17

*AIS 6 recoded to represent fatalities.

TABLE 4-34. NUMBER OF INJURIES AND FATALITIES AND PERCENT BENEFIT IN THE YEAR 1990 BY RADAR SYSTEM - VEHICLE-TO-VEHICLE SIDE

		Number of Injuries and Percent Benefit							
	Baseline	System 2		System 3		System 4		System 5	
AIS	System	No.	%	No.	%	No.	%	No.	%
1	12,468	12,029	4	12,038	3	12,180	2	12,180	2
2	1,542	1,492	3	1,492	3	1,512	2	1,512	2
3	1,090	1,054	3	1,055	3	1,070	2	1,070	2
4	189	183	3	183	3	186	2	186	2
5	71	69	3	69	3	70	1	70	1
6*	242	235	3	235	3	238	2	238	2
Total	15,602	15,062	4	15,072	3	15,256	2	15,256	2

*AIS 6 recoded to represent fatalities.

TABLE 4-35. NUMBER OF INJURIES AND FATALITIES AND PERCENT BENEFIT IN THE YEAR 1990 BY RADAR SYSTEM - VEHICLE-TO-VEHICLE REAR

		Number of Injuries and Percent Benefit							
	Baseline	System 2		System 3		System 4		System 5	
AIS	System	No.	%	No.	%	No.	%	No.	%
1	2,974	1,310	56	2,071	30	1,103	63	1,103	63
2	132	52	61	82	38	46	65	46	65
3	37	12	68	20	46	12	68	12	68
4	15	6	60	10	33	5	67	5	67
5	2	1	50	1	50	1	50	1	50
6*	32	7	78	12	63	8	75	8	75
Total	3,192	1,388	57	2,196	31	1,175	63	1,175	63

*AIS 6 recoded to represent fatalities.

TABLE 4-36. NUMBER OF INJURIES AND FATALITIES AND PERCENT BENEFIT IN THE YEAR 1990 BY RADAR SYSTEM - ALL CONFIGURATIONS (KSPTYP = 1-6)

		Number of Injuries and Percent Benefit							
		System 2		System 3		System 4		System 5	
AIS	Baseline System	No.	%	No.	%	No.	%	No.	%
1	36,998	31,989	14	33,540	9	32,386	13	32,244	13
2	6,660	5,969	10	6,091	9	6,054	9	6,019	10
3	3,046	2,786	9	2,827	7	2,839	7	2,818	8
4	560	508	9	515	8	518	8	512	9
5	228	210	8	211	8	214	6	212	7
6*	778	703	10	711	9	717	8	709	9
Total	48,270	42,165	13	43,895	9	42,728	12	42,514	12*

*AIS 6 recoded to represent fatalities.

TABLE 4-37. DOLLAR COST AND RELATIVE DOLLAR BENEFIT BY RADAR SYSTEM (MILLIONS OF 1979 DOLLARS)

		Dollar Cost and Relative Dollar Benefit							
		System 2		System 3		System 4		System 5	
Accident Configuration	Baseline System	$	%	$	%	$	%	$	%
FOF	48.5	40.4	17	41.2	15	41.2	15	41.2	15
FOS	46.9	46.9	0	46.9	0	46.9	0	46.9	0
FOR	93.5	93.5	0	93.5	0	93.5	0	93.5	0
VVF	101.1	80.6	20	83.5	17	85.6	15	81.7	19
VVS	142.4	138.0	3	138.0	3	139.9	2	139.9	2
VVR	18.3	5.9	68	9.6	48	5.6	69	5.6	69
Total	450.6	405.0	10	412.3	9	412.3	9	408.5	9

relative distribution over injury levels and the relative radar system benefits are not significantly altered in 1990 compared to 1978.

4.9 ANALYSIS OF NASS HARDCOPY

The analysis of hard-copy accident reports from the NASS system is a useful complement to the computerized analysis of the North Carolina accident data which is carried out by the Radar Brake Algorithm. Analysis of a hardcopy report allows a more detailed and precise description of vehicle trajectories than does the computerized analysis, and it is possible in the hardcopy to ascertain causal factors, driver actions, and the effects of pre-impact events in general. The essential components of the hardcopy records in NASS are the following items:

1. The Annotated Accident Collision Diagram showing the pre-impact, impact, and post-impact positions and loadings of the vehicles and relevant objects and roadways;
2. The Police Report Accident Description containing a narrative of the accident events and descriptions of driver actions and probable causes; and
3. The Driver Form containing the driver's description of the accident, the pre-accident driver actions and attempted avoidance maneuvers, and the estimated travel and impact speeds.

Unfortunately, NASS protocols have resulted in the police reports and the driver accident description not being available for analysis. Under the circumstances, it is still possible to refer to the collision diagram and other driver pre-impact data. This report illustrates the results of an examination of two typical NASS cases.* Further research along these lines is contained in Appendix M, where hard-copy FARS cases are considered.

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*The case selection process is documented in Kinetic Research Technical Note KR-TN-012, "Selection of Hardcopy NASS Cases for Use on Contract No. DTNH22-80-R-07062."

The hard-copy case analysis is intended primarily for the understanding of questionable or difficult to analyze accident circumstances such as those involving off-road objects, turning vehicles, etc. Therefore, this analysis is based on engineering judgement applied to individual cases without attempting a tabulation or statistical analysis.

Case 02-027H involved a pickup truck which failed to stop at a T-intersection, left the crossing road at a perpendicular angle, and struck a tree 40 feet beyond the side of the road. The estimated vehicle travel speed was 60 mph and no driver actions were indicated. Vehicle damage was front center, narrow impact, with a prinicipal force direction of 5 degrees. The computed Delta-V was 11.7 mph. The most severe occupant injury was AIS 2. If one assumes that the vehicle speed was reduced from 60 mph to 12 mph in the 40 feet of off-road travel, one would require a mean deceleration of approximately 3 Gs. This is possibly compatible with vehicle travel over rough ground which might contain small objects (rocks, logs, etc.).

If a radar unit could detect a tree directly ahead, it is likely that this impact would be avoided. Using a control law such as $R_B = R^2/2\mu g$ with $\mu = 0.5$ gives $R_B = 240$ feet. Assuming a radar range maximum of 200 feet and 40 feet of off-road travel, there would still be 160 feet of on-road braking, which would reduce the vehicle speed from 60 mph to about 35 mph before leaving the road. At 3 Gs off-road, the truck would then stop in roughly 30 feet and impact would be avoided. It is questionable whether or not typical radar units would see an object such as a single tree at any useful range. A consideration is that if a guardrail or warning sign were in existence on the far side of the crossing road, the radar might very well trigger on that object and effectively avoid the accident. In any case, this example illustrates a particular example of a fixed-object impact which occurs even though the subject vehicle travels forward in a straight line without loss of control. Further, this accident is similar to the typical rear-end impact involving driver inattention or failure to slow and stop as required. No driver incapacitation was indicated.

In case 02-044H, Vehicle 1, a pickup truck, was overtaking Vehicle 2, a stationwagon, on the left when Vehicle 2 turned left in front of Vehicle 1 and was struck in the side. Vehicle 1 attempted to brake and steer to the left, but nevertheless impacted at approximately 30 mph which was also the estimated travel speed. Vehicle 2's speed was 10 mph or less. There is no evidence of driver incapacitation for either driver. The calculated Delta-V was 3.9 mph.

In this accident, it is unlikely that a radar braking system would have been helpful, as the struck vehicle came into the radar beam too close to the striking vehicle to be avoided. This is evidenced by the fact that attempted driver actions neither avoided nor mitigated the collision.

Further NASS cases can be analyzed in a similar manner, but the absence of critical information precludes the value of doing that was expected to be obtained originally. Previous analysis of a set of FARS hard-copy cases is included as Appendix M. These cases have police report accident descriptions and diagrams but not the complete quantitative case data that would be sought in NASS.

SECTION 5
SUMMARY AND CONCLUSIONS

5.1 SUMMARY AND CONCLUSIONS

The work under this contract can be divided into two major parts, the radar system technical evaluation and the analysis of radar braking system benefits. This is in addition to the preliminary review of previous cost-benefit analyses and the selection of an evaluation methodology, which were completed at the beginning of the contract.

The radar technical evaluation is concerned with three areas:

- Ability of given radar systems to detect and discriminate targets;
- The relative immunity of each given system to false alarms; and
- The cost to implement a given radar system in a large fraction of the vehicle population.

The results of the radar system technical evaluation showed that the signal processing technique and the control laws used were the key parameters that influenced the ability of a system in terms of target discrimination, the avoidance of false alarms, and the missed targets. Based on the system performance studied, the systems were grouped into three levels according to their signal processing technique and control laws.

The analysis of radar braking system benefits is based on the computerized reconstruction of a set of actual motor vehicle accidents which are roughly representative of national experience. The output of this analysis is a tabulation of property damage and of injuries and fatalities that would occur if the vehicles involved in the subject accidents had been equipped with radar braking systems designed to mitigate collision severities or to avoid accidents by the timely automatic application of brakes.

The radar system performance is represented in the analysis by the braking system control law which characterizes each system. The characteristics of the three levels of radar system performance are not directly reflected in the benefit analysis, except insofar as one or another control law might be implemented at a given level. Rather, our view is that the technical sophistication of the radar system will mainly affect the ability to reject false alarms at a given level of detection efficiency. The control law is a criterion relating separation between the radar-equipped vehicle and another vehicle or object to the speeds of travel of the involved vehicles which determines whether or not radar brake activation should occur. The control laws used in this analysis were:

System One: No radar

System Two: $R_B = 2\dot{R} + S$

System Three: $R_B = \dot{R}^2/2\mu g + \tau\dot{R} + S$

System Four: $R_B = V_1^2/2\mu g - V_2^2/2\mu g + \tau V_1 + S$

System Five: $R_B = 1\ V_1^2/2\mu g + V_2^2/2\mu g + \tau V_1 + S$ (head-on only)

(all units in feet, seconds) $R_B = V_1^2/2\mu g + . . .$

where

R_B	=	Range at which radar braking would begin;
$\dot{R}$	=	Range rate or rate of approach of the target;
V_1, V_2	=	vehicle speeds
μg	=	Potential vehicle deceleration based on the surface coefficient of friction;
τ	=	Radar time delay; and
S	=	Radar range delay.

In practice, the analysis has been performed for the values $S = 0$, $\tau = 0.1$, and $\mu = 0.5$. In addition, the radar braking range is cut off at 200 feet maximum, and the radar system shuts off if the vehicle velocity falls below 10 mph. It is assumed that all objects bearing within 0.05 radian of the beam axis and closer than 200 feet are detected by the radar system. In this sense, the detection capability of the radar system is not directly considered in the benefits analysis. The accident reconstruction algorithm imposes one further condition, namely, that there is a time delay of 0.1 second between target detection and brake application. The delay can be increased to a larger value (say 1.0 second) to reflect the performance of a driver warning system. This value has been used in a partial analysis concerning property damage losses only. The vehicle braking systems are also considered to have an anti-skid feature in that the effective coefficients-of-friction under radar braking are increased relative to those estimated for the actual accidents. The predicted results and relative benefits are presented in Table 5-1. It can be seen that radar systems are potentially very effective in rear impact accidents. This is the area in which benefits from radar braking have traditionally been anticipated. The rationale for this result is that rear impact configurations afford the radar system a good target detection and tracking geometry, and that it is suspected that many or most rear-impact collisions are the result of driver inattention or poor judgement and could be avoided under many circumstances.

Vehicle-to-vehicle front impacts show lesser, but still significant results. One must note that the accident configuration definitions used in this study are based on case vehicle damage areas. Thus "front impacts" can include head-ons, the striking vehicle in front-to-side impacts, and the striking vehicle in front-to-rear impacts.

The results for rear impacts quoted above are for the struck vehicles only.

Fixed-object front impacts show benefits similar to vehicle-to-vehicle front impacts. In these cases the radar systems are assumed to be effective in the detection of and reaction to objects up to 10 feet off the road. This is based on the evident fact that, in the actual accident, the case vehicle must indeed have been headed directly at the struck object at some time. Cases where there is vehicle loss of control or skidding are excluded from potential benefit.

Vehicle-to-vehicle side impacts represent struck vehicles in front to side collisions. The benefits in this case represent the benefit to struck vehicles of radar systems on the striking car. These benefits are limited by the fact that the radar systems are assumed not to be able to detect objects bearing more than 0.05 radian from the radar central axis. Most side impact configurations occur at bearings of 30 to 50 degrees, or approximately 0.5 radian.

Fixed-object side and rollover/non-collision modes are assumed by definition to be unaffected by radar braking systems. The data for these modes are carried

TABLE 5-1. SUMMARY OF BENEFITS FOR RADAR SYSTEMS SHOWING THE NUMBER AND PERCENT OF INJURIES, ACCIDENTS AND PROPERTY DAMAGE AVOIDED

Radar System Two[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	710	11	1.4	16	367	12	151	17	58	17	9	16	7	20	10	18	602	14
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ROLL/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	6,270	19	3.9	17	2,042	18	310	17	105	18	93	19	7	23	23	24	2,509	18
VVS	1,122	4	1.1	6	363	4	40	3	30	3	5	3	2	3	6	3	446	4
VVR	2,664	53	1.2	51	1,380	56	65	60	29	67	7	58	2	100	19	76	1,493	56
Ped[4]	487	14	0.2	15	239	13	65	14	43	14	12	15	5	15	42	26	406	14
Total	11,253	7.8	13	12	4,392	14	632	11	256	9	54	10	23	10	100	13	5,457	13

[1]Defined by the control law $R_B = 2\dot{R}$.
[2]Includes accidents with AIS = 0 injuries.
[3]In millions of dollars.
[4]Tabulated for unmodified Vrel.

TABLE 5-1. (Cont'd)

Radar System Three[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	73	1	1.0	10	149	5	134	15	49	15	9	16	7	20	10	18	358	8
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roll/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	4,802	15	3.4	15	1,612	14	251	14	88	15	19	17	6	19	21	22	1,997	14
VVS	1,084	4	.8	4	356	3	40	3	29	3	5	3	2	3	6	3	438	3
VVR	1,291	26	.7	29	749	30	41	38	14	47	4	33	1	50	16	64	825	31
Ped[4]	419	12	.1	13	202	11	56	12	38	13	10	13	4	12	41	25	351	12
Total	7,669	9	5.9	9	3,032	9	523	9	218	8	47	9	20	9	94	12	3,934	9

[1]Defined by the control law $R_B = \dot{R}^2/2\mu g + \tau\dot{R}$.
[2]Includes accidents with AIS = 0 injuries.
[3]In millions of dollars.
[4]Tabulated for unmodified Vrel.

TABLE 5-1. (Cont'd)

Radar System Four[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	73	1	1.0	10	148	5	134	15	49	15	9	16	7	20	10	18	357	8
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roll/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	6,018	18	3.5	15	1,884	16	268	15	83	14	15	13	5	16	15	16	2,270	16
VVS	791	3	.6	3	238	2	24	2	17	2	3	2	1	2	4	2	287	2
VVR	3,117	62	1.4	59	1,553	63	70	65	21	70	8	67	2	100	18	72	1,672	63
Ped[4]	462	13	.1	14	225	12	62	13	41	14	11	14	5	15	42	26	386	13
Total	10,561	12	6.6	10	4,050	12	559	9	211	7	46	9	20	9	89	11	4,975	12

[1]Defined by the control law $R_B = V_1^2/2\mu g - V_2^2/2\mu g + \tau V_1$.
[2]Includes accidents with AIS = 0 injuries.
[3]In millions of dollars.
[4]Tabulated for unmodified Vrel.

TABLE 5-1. (Cont'd)

Radar System Five[1]

Accident Configuration	Accident Involvements Avoided[2]		Property Damage Reduction		Injuries Avoided (by AIS)													
					1		2		3		4		5		6		Total AIS 1-6	
	No.	%	$[3]	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
FOF	73	1	1.0	10	149	5	134	15	49	15	9	16	7	20	10	18	358	8
FOS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roll/NC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VVF	6,255	19	3.8	17	2,001	17	298	16	100	17	20	17	6	19	21	22	2,496	17
VVS	791	3	.6	4	237	2	23	2	17	2	3	2	1	2	4	2	285	2
VVR	3,117	62	1.4	59	1,553	63	70	65	21	70	8	67	2	100	18	72	1,672	63
Ped[4]	479	13	.2	15	234	12	64	14	42	14	12	15	5	15	43	26	400	14
Total	10,715	13	6.9	11	4,177	13	590	10	229	8	52	10	21	9	96	12	5,165	12

[1]Defined by the control law $R_B = V_1^2/2\mu g \pm V_2^2/2\mu g + \tau V_1$ (+ for head-on; otherwise -).
[2]Includes accidents with AIS = 0 injuries.
[3]In millions of dollars.
[4]Tabulated for unmodified Vrel.

through so that relative proportions of accidents by configuration will be evident in the tables.

Examination of the overall benefits achieved reveals one important feature of the radar braking system performance. This is that the greatest relative benefit occurs in the accident configuration which contributes the least to overall societal loss. The two most significant configurations, vehicle-to-vehicle front and vehicle-to-vehicle side, are less affected or not affected. Even non-motorist collisions do not represent a large area of loss, and we have commented that in reality there may be no benefits at all in this mode.

In Section 4.2, Tables 4-26 through 4-28, the question of the sensitivity of the results to the control law parameters is discussed. The most significant questions are how the benefits would be affected by the maximum radar range value and by the brake system time delay. It is seen that 200 feet is a reasonable range cut-off because extension of the range to 400 feet does not add much benefit, whereas reduction of the maximum range to 100 feet results in a significant loss of benefit. The question of brake system time delay has to do with the possible performance of the system if the radar were a warning only system and a driver reaction time for braking of 1.0 second is assumed. In this case, there is considerable degradation of the collision avoidance and mitigation potential of the system. This conclusion does not consider the possibility that a radar warning system might operate in such a way as to provide warnings sooner than actual automatic braking would ensue. This subject might be addressed by running the benefits model with altered control laws, but has not been dealt with in detail in this study.

The four different radar control laws considered all show substantial benefits in certain areas and also some differences in effectiveness. The differences in the laws pertain to whether or not the braking range is calculated from velocities to the first power or from velocities to the second power (System 2 versus System 3 through 5), and to whether the system is sensitive to relative velocities or actual vehicle speeds (Systems 2 and 3 versus Systems 4 and 5). System 5 is essentially System 4 except that the behavior of the system in the head-on configuration has been changed to respond to the absolute sum of the speed terms rather than the absolute difference. This change has little effect, as very few impacts in the vehicle-to-vehicle front configuration are actually head-on.

Figures 4-9 through 4-16 illustrate the forms of the different control laws. It can be seen that the quadratic laws give much shorter ranges for brake activation at lower speeds in the rear-impact configuration (especially for System 3). This explains the particularly poor performance of System 3 in the vehicle-to-vehicle rear configuration. Other differences in results can be traced to the actual behavior of the control laws relative to the frequency of occurrence of different impact speeds and configurations.

Table 4-6, which presents the accident avoidance results by radar brake configuration as well as by KRAESP accident type, demonstrates that the analysis is determined very largely by whether or not the accident configuration permits radar system operation at all. The majority of accidents considered are classed CONFIG=NULL meaning that, for one reason or another, the radar system is not operable in that situation (see Section 4.3). In those cases where radar does function, the accident is very often avoided entirely. These circumstances largely explain why, by-and-large, the normalized Vrel frequency distributors (which exclude accidents which have been avoided) do not show large changes from no radar to the various systems. Larger shifts are noticed in fixed-object front than elsewhere. These circumstances also reveal that radar system performance benefit is highly dictated by the frequency of inappropriate circumstances and that improvements or degradations in system performance will have reduced impact when considered over all situations. At the same time, one should note that the results of the radar brake algorithm are as much or more sensitive to the classification of accidents as to the radar performance characteristics. The accident classification is, in turn, dictated by the availability and accuracy of the data in the subject files. Validation of the current results using alternative information will be possible for future studies.

The results obtained pertain to a subset of actual accidents occurring in North Carolina in 1979. This subset is the set of accidents for which sufficient information was known in order to accomplish the accident reconstruction. The total number of accidents so considered may be obtained from Table 4-6 along with the total numbers of cases originally in the data file. The original accident cases have been adjusted by a case weighting method to reflect characteristics of the national experience as seen in the NASS file (see Appendix D). This representativeness is approximately maintained by the subset of "known" cases (see Section 4). These results can be expanded to national estimates in proportion to the ratio of national accidents to case accidents. The relative benefits would not, of course, be affected. Certain assumptions used in the KRAESP Model to predict injuries and fatalities have required substantial adjustments to be made to the Vrel distributions computed in the Radar Brake Algorithm. The validation of the adjustments lies in the comparison of actual North Carolina injuries and fatalities to System 1 (no-radar) predictions. The comparison is close but could be improved by further adjustments. If further analysis along these lines were to be considered, it is suggested that the KRAESP Model be used with revisions to the Occupant Injury to Crash Severity tables currently available. Alternatively, motor vehicle occupant injuries could be estimated directly from the Vrel data in the same manner as the property damage and non-motorist injuries, as were obtained on this program.

The evaluation of benefit degradation due to false alarms is inherently beyond the scope of the benefit methodology used in this study. The reason for this is that the study is based on the examination of existing accidents, the statistical incidence and severity of which is known and which may be considered to be selectively mitigated or avoided. There is no way that one can obtain from a set of known accidents a statistical sample of new accidents which would be caused by a hypothetical system. This situation is subject to some important considerations, however. It is generally agreed that for public acceptance and security against product liability action, no practical automatic radar braking system will be implemented which shows false alarms at any more than a fraction of the rate at which true alarms are experienced. In this sense, there is no false alarm problem. In point of fact, the necessity of avoiding false alarms places restrictions on the performance of the system, such as the maximum accepted radar range and the shutdown of radar systems if there are steering inputs. These factors have been taken into account in this analysis. Also, the effects of reduction in maximum range have been examined.

The injury and fatality predictions for the different radar systems have been scaled by the assignment of dollar loss to each injury level. When these costs are distributed over all the vehicles at risk and compared to analyzed cost of installing the systems, it is found that the radar system cost-benefit index is negative. There is a marginally greater cost for installing the systems than there is benefit from the use of such systems. The cost-benefit trade-off is illustrated in Figure 5-1.

Within the accuracy of the analysis, the conclusion of this study would be that the benefits obtained from automotic radar braking systems can be roughly equal to the costs of installing such systems.

5.2 RECOMMENDATIONS

1. During the course of the program, it was expected that actual test and system performance data will be available from an on-going NHTSA program and from the radar system developers. The information was available was very sketchy and incomplete. It is recommended that the available radar braking systems be subjected to comparative test evaluation to determine their performance for key parameters such as false alarm rate, missed targets, target discrimination, non-motorist detection, etc. The actual performance data then could be used with the methodology developed here to obtain a further improved and more realistic cost-benefit evaluation.

2. The current program was not scoped to address the cost-benefit evaluation of the radar systems for non-passenger cars such as trucks. Non-passenger cars, in general, are heavy users of highways. Their initial cost is high, making the radar system a very small fraction of their initial cost. These factors suggest that radar systems can be beneficial and attractive to the heavy vehicle operators. The drivers of heavy trucks have long driving hours, under all sorts of environmental conditions. Radar braking systems are likely to be a good and safe driving aid to them. A detailed cost-benefit analysis of radar braking systems on trucks, using the methodology developed on this program, is highly recommended.

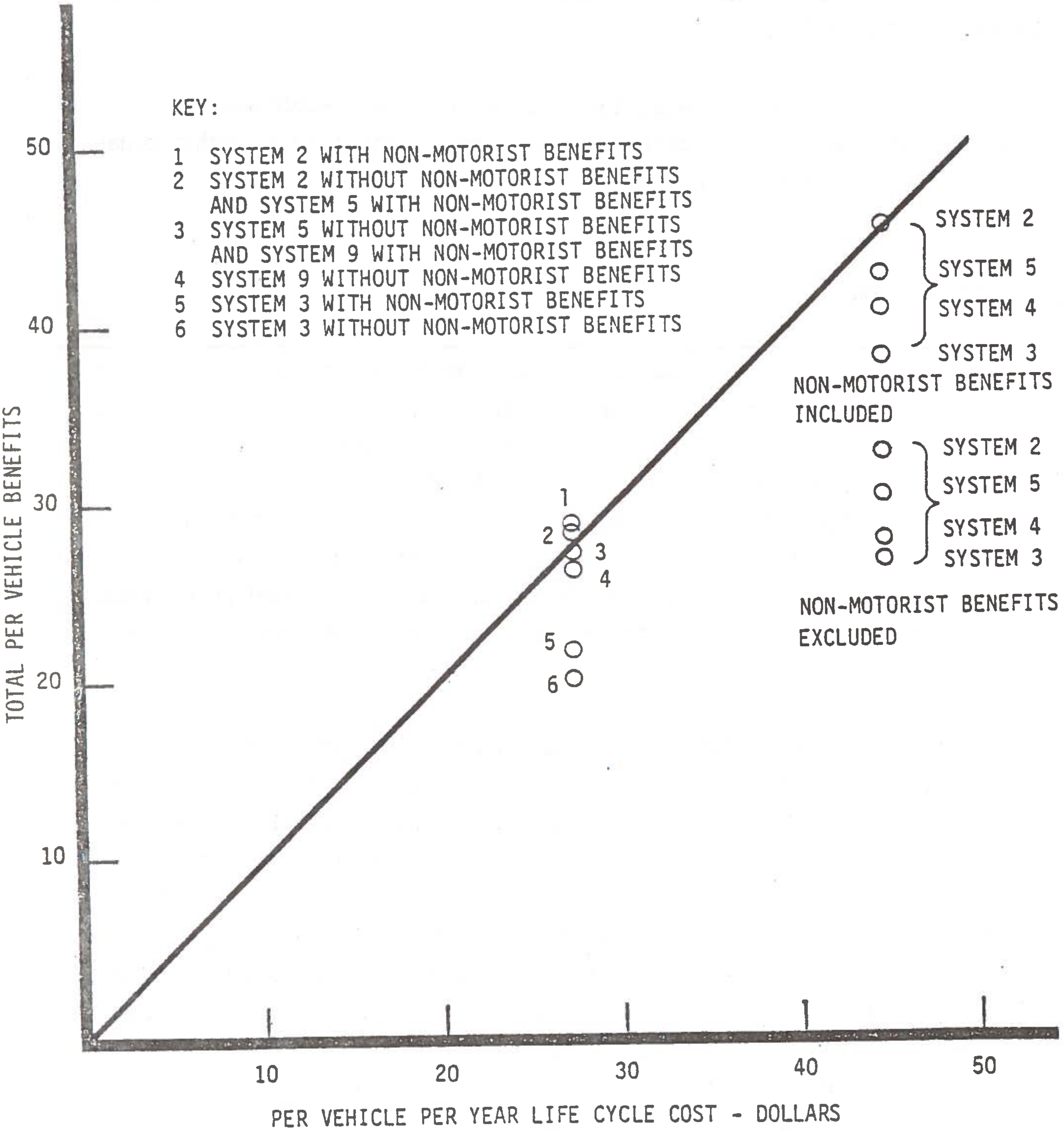

FIGURE 5-1. COST EFFECTIVENESS COMPARISON FOR FOUR RADAR SYSTEMS

3. Other categories of vehicles that appear to have potential for radar braking systems are taxicabs, emergency vehicles, and buses. All these vehicles are heavy users of roads and encounter inclement environmental conditions more frequently than do the passenger cars. The drivers of these vehicles can definitely benefit from the radar braking systems.

4. There is a definite trend toward an increase in use of electronic components, such as cruise control, diagnostic and status display, electronic ignition, etc. in automobiles. This presents a tremendous opportunity to "piggyback" radar systems as a part of source of these systems. This would enable the component cost-sharing among these systems, thus providing substantially lower costs. Moreover, such electronic systems appear to have consumer appeal and industry approval.

5. One drawback encountered on this program was the inability to use the NASS data file. The proportion of missing Delta-Vs was found to be very large, making the 1979 NASS file inappropriate for this program. The hardcopy analysis of selected NASS cases further revealed that the "sanitization" process had eliminated much useful background information on the pre-crash factors that are not computerized.

REFERENCES

1. The Bendix Corporation, "Collision Avoidance Radar Braking Systems Investigation – Phase II Study, Volume I – Summary Report," Contract No. DOT-HS-4-00913, February 1976.

2. The Bendix Corporation, "Collision Avoidance Radar Braking Systems Investigation – Phase II Study, Volume II – Technical Report," Contract No. DOT-HS-4-00913, September 1976.

3. Institute for Research in Public Safety, "Tri-Level Study of the Causes of Traffic Accidents: Interim Report II (Volume II: Radar and Anti-Lock Payoff Assessment)," Indiana University, 1975.

4. Indiana University, "An Assessment of the Accident Avoidance and Severity Reduction Potential of Radar Warning, Radar Actuated, and Anti-Lock Braking Systems," 1977.

5. K. Friedman, "BRAKE Algorithm Documentation," KRI-TR-020, December 1977.

6. L.E. Wood, R.A. Chandler and B.D. Warner, "Analysis of Problems on the Application of Radar Sensors to Automotive Collision Prevention," Report No. DOT-HS-801-451, U.S. Department of Commerce, Institute for Telecommunication Sciences, March 1975.

7. V. Ausherman and K. Friedman, "Review of Collision Avoidance Cost-Benefit Analyses." Kinetic Research Technical Report KR-TR-073, November 1980.

8. "The National Accident Sampling System, A Status Report, Vol. III, Implementation of NASS Subsystems." U.S. Department of Transportation, National Highway Traffic Safety Administration, December 1978.

9. G. Demos, S. Kazel, et. al., "Collision Avoidance Radar Braking System Investigation (Phase I)," Final Report, U.S. Department of Transportation, National Highway Traffic Safety Administration, Contract DOT-HS-4-00935, December 1974.

10. M. Kiyoto, N. Fujiki, et. al., "A Study of the Automatic Braking System", Seventh International Conference on Experimental Safety Vehicle, Paris, June 1979.

11. E.F. Belohoubek, J.J. Risko, et. al., "Electronic Subsystems for the Research Safety Vehicle (RSV) Phase III," RCA Laboratories Report PRRL-80-CR-8, March 1980.

12. Letter from Bendix Corporation to Minicars, Inc. dated 13 June 1980.

13. R.E. Freiman, "PRICE – A Parametric Cost Modeling Methodology," RCA Government and Commercial Systems, May 1978.

14. V. Ausherman and A. Khadilkar, "Selection of Accident Data Base and Accident Analysis Approach for Collision Avoidance System Benefit-Cost Analysis," Kinetic Research Technical Report KR-TR-083, December 1980.

15. D. Redmond, "Preliminary Analysis of the 1979 NASS File for Contract DTNH22-80-C-07530, 'Collision Avoidance System Cost-Benefit Analysis,'" Kinetic Research Technical Report KR-TR-099, March 1981.

16. D. Redmond, "Implementation and Preliminary Analysis of 1979 State of North Carolina Accident Data for Use on Contract DTNH22-80-C-07530, 'Collision Avoidance System Cost-Benefit Analysis,'" Kinetic Research Technical Report KR-TR-103, March 1981.

17. D. Redmond and K. Friedman, "Introduction to the Kinetic Research Accident Environment Simulation and Projection (KRAESP) Model," Kinetic Research Technical Report KR-TR-041, January 1980.

18. P. Dougan and K. Friedman, "User's Manual for the Kinetic Research Accident Environment Simulation and Projection (KRAESP) Model, Version 3," Kinetic Research Technical Report KR-TR-066, December 1980.

19. D. Redmond, "Adjustments Made to the 1979 North Carolina Data to Make it Nationally Representative," Kinetic Research Technical Note KR-TN-013, May 1981.

20. D. Redmond, "Calculation of the Projected Benefits of Upgraded Restraint-Structure System Performance Using the KRAESP Model," Kinetic Research Technical Report KR-TR-067, September 1980.

21. L. Klimko, "Development of an AIS to Delta-V Relationship for Vans and Light Trucks," Kinetic Research Technical Report KR-TR-095, January 1981.

22. Bendix Corporation, "Braking Performance Analysis," Contract PO-A-33529, July 1973.

23. Automotive Industries, A Chilton Publication, September 1981.

24. U.S. Department of Transportation, National Highway Traffic Safety Administration, "1975 Societal Costs of Motor Vehicle Accidents."

25. Division of Motor Vehicles, North Carolina Department of Transportation, "North Carolina Traffic Accident Facts — 1979."