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Potential Safety Applications of Advanced Technology

Final Report

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FOREWORD

This report will be of interest to highway engineers responsible for the application of new technology. The purpose of this study was to identify and evaluate the applications of new technology to known highway safety problems including the assessment of their functional requirements, feasibility, costs, and potential safety benefits. The emphasis was on countermeasure systems that are roadway based.

A collision typology was run on NHTSA's CARDfile (Crash Avoidance Research Data file). Based on the CARDfile analyses, six collision types were selected as targets for the application of advanced technology to improve safety. Eighteen countermeasures were developed which were aimed at the six accident types. Four of the countermeasure systems apply generally to all six crash types. The other fourteen countermeasure systems are aimed at factors involved in individual accident types. Cost and benefit estimates were made for the eighteen countermeasures.

Two copies of this report are being sent to each region, and six copies are being sent to each division office. At least four of these copies sent to the division should be sent to the State highway agency by the division office.

Lyle Saxton, Director
Office of Safety and Traffic
Operations Research and Development

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16. Abstract
This report identifies and evaluates the application of new technology to known highway safety problems, including an assessment of functional requirements, feasibility, costs, and potential safety benefits.

Findings are documented for the following subjects: (1) a typology of prevalent accident/crash types, (2) functional descriptions of 18 postulated countermeasure systems for mitigating the consequences of prevalent crash types, (3) the relationship of advanced technology to the sensing, processing, communications, and display needs of the postulated countermeasure systems, (4) potential safety benefits of countermeasure systems as expressed by estimates of the reductions in risk and severity in selected accident types, and (5) estimates of the costs of countermeasure systems and their rate of penetration into the driver-vehicle-roadway system.

Conclusions and recommendations concerning the development of safety applications of advanced technology are delineated in chapter 8 of the report. The crash countermeasures identified as having high safety potential are headway control for rear-end crashes, lane-edge detection for run-off-road situations, lane-keeping systems, night vision enhancement as a crosscutting measure for various crash types, longitudinal control for pedestrians, cyclists, animals, etc. in the road, and impaired driver warnings as a crosscutting measure for various crash types.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	ac
ha	hectares	2.47	acres	mi^2
km^2	square kilometers	0.386	square miles	
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised August 1992)

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CHAPTER 1. INTRODUCTION

The purpose of this report is to document the findings of a study whose objective is to identify and evaluate the application of new technologies to known highway safety problems. It includes an assessment of their functional requirements, feasibility, costs, and potential safety benefits. [1]

The thesis of this study is that the development of intelligent vehicle/highway systems (IVHS) and related advanced technology offers a number of opportunities to improve highway safety, particularly as applicable to specific safety problems. The goal of the work reported here is to aid in the process of applying new technology for achieving safety benefits through crash prevention countermeasures. To that end, there is a need to be able to assess the potential uses of advanced technology in order to identify those areas that would have significant impact on accident frequency and severity and target them for early development and deployment.

The new safety enhancement strategies and countermeasure systems developed in the future are expected to include both roadway and in-vehicle applications and combinations thereof. And, indeed, the countermeasure systems described later in this report involve strategies that are roadway- or vehicle-based or cooperative in nature. Nevertheless, the application of new technology to the roadway system has been an underlying theme in selecting several examples of candidate countermeasure systems that are roadway-based in the sense that they fit in with the concept of a "smart" roadway system.

In that regard, the study has had a roadway thrust from its inception and in its later direction. The rationale for this aspect of the study is as follows:

The application of new technology to the roadway system to provide useful, up-to-date, and meaningful warning-and-control information based on current roadway, traffic, and environmental conditions is seen as a fertile area for achieving safety benefits. The development of the smart roadway system should be in harmony with the evolving development of IVHS. On existing highways, warning and control information is provided through a series of signs, signals, and pavement markings known as traffic control devices. Most of the signs and markings are static, meaning that the messages never change. Some also lack adequate visibility. However, to properly assist the driver, warning-and-control device information needs to be recognized, understood, timely, and credible, based on roadway, traffic, and environmental conditions. Therefore, using new technology, traffic control methods, and devices should be developed to improve the driving information system and provide a smart roadway system.[1]

The findings of this study include: (1) identifying prevalent crash types, (2) developing descriptions of postulated countermeasure systems, (3) relating these systems and their functional requirements to advanced technology, and (4) assessing reductions in risks and severity in selected crash types. The next chapter (chapter 2) of this report describes the methodology that has evolved during this project. In a broad sense, the development of a workable methodology constitutes a finding of the study. Given that there is a developing process for synthesizing, designing, and evaluating crash prevention systems, an understanding of the methodology used in this study may be as important for its own sake as it is for putting the various findings of the study in a documented context.

Findings with regard to identifying prevalent crash types are presented in chapter 3. Postulated crash prevention and avoidance countermeasures are described in chapter 4. The countermeasure systems are classified as "crash type specific" and "cross-cutting," thereby distinguishing those that address one type of crash from those that influence the outcomes of crashes in general.

Inherent in the creative process of postulating countermeasure systems, there is involved, at least implicitly, some form of a theory of driving. Although this aspect of the project was not formalized when the countermeasure systems were postulated, certain basic features of a very elementary theory of driving are presented in the beginning of chapter 4 in order to provide a basis for documenting the rationale behind the countermeasure systems. (The terms *philosophically logical* or *philosophical logic* might be used to refer to reasoning based on the theory of driving.)

Chapter 5 provides a review of existing advanced technologies and discusses the functional requirements of these technologies as well as the application of these technologies to the postulated countermeasure systems.

The evaluation of the countermeasure systems as to their potential safety benefits is presented in chapter 6. Matters concerning costs, feasibility, reliability, time frames, and shortcomings are documented in chapter 7. Conclusions and recommendations concerning development and deployment of countermeasure systems that are predicted to have a significant impact on crash frequency and severity are presented in chapter 8.

CHAPTER 2. OUTLINE OF METHODOLOGY

The methodology used in this study included a creative step in which crash prevention and avoidance countermeasures were formulated. This creative process was guided by results from analysis of accident data and the factors associated with prevalent types of crashes.

Several brainstorming sessions were conducted to aid in hypothesizing the features of possible countermeasure systems that would address the safety problems identified by analyzing the accident data. The participants in these sessions included members of the project team with expertise in a broad range of pertinent disciplines, such as:

- Vehicle dynamics.
- Human factors.
- Highway design and engineering.
- Sensor technology and remote sensing.
- Electrical engineering and computer science.
- Accident data, statistics, and analysis.
- Control systems and theory.

In addition, outside experts in law enforcement, highway engineering, and motor vehicle enforcement participated in the brainstorming activities.

Nevertheless, details of the countermeasure systems presented herein are primarily the work of two or three people in each case. Attempts at including more people in the process of specifying a countermeasure system tended to be counterproductive in terms of focusing on the functions of a particular system and how those functions might be implemented. It proved to be very difficult for people to agree on the details of a countermeasure system even though they agreed in concept with the idea of developing a particular type of crash prevention countermeasure. Hence, the systems described in chapter 4 may be viewed as examples of countermeasure systems with two general characteristics: (1) they are based on addressing safety problems identified through a study of crash data, and (2) they are candidates for further evaluation in terms of their functional requirements, feasibility, potential safety benefits, and costs.

The set of countermeasure systems, developed by the process just outlined, includes approximately eighteen different systems (depending upon how one counts variations of them).[2] This set of systems provided the raw materials that have been evaluated in the later stages of this project and in the preparation of this report. The conclusions and recommendations of this report are based on both the understanding and information gained in: (1) formulating countermeasure systems and (2) evaluating countermeasure systems.

In hindsight, it is easier to outline the methodology used than it was to develop it in the first place. Although the steps performed in this study may appear to be straightforward and logical, they were not at all apparent during the time when the researchers were attempting to be inventors of countermeasure systems. The distinctions among establishing functional requirements, synthesizing systems, selecting technology, and evaluating proposed systems were not clearly understood. There seemed to be a need to address all of these activities simultaneously and there never seemed to be enough information to do any one of these activities. Perhaps, the above is nothing more than a description of the challenges to be met when a creative process is involved.

In summary, the steps constituting the methodology used in this study are as follows:

1. Build a crash typology.[3]
2. Examine factors associated with prevalent crash types.
3. Postulate countermeasure systems.
4. Develop functional requirements.
5. Inventory technology for application to functional requirements.
6. Assess potential safety benefits and costs.
7. Document findings and present conclusions and recommendations.

Figure 1 provides an overview showing in concept how analyses of crash data and a knowledge of technology may come together to enable a synthesis of countermeasure systems. This figure provides a general idea of the methodology that we were striving for while we were conducting this project.

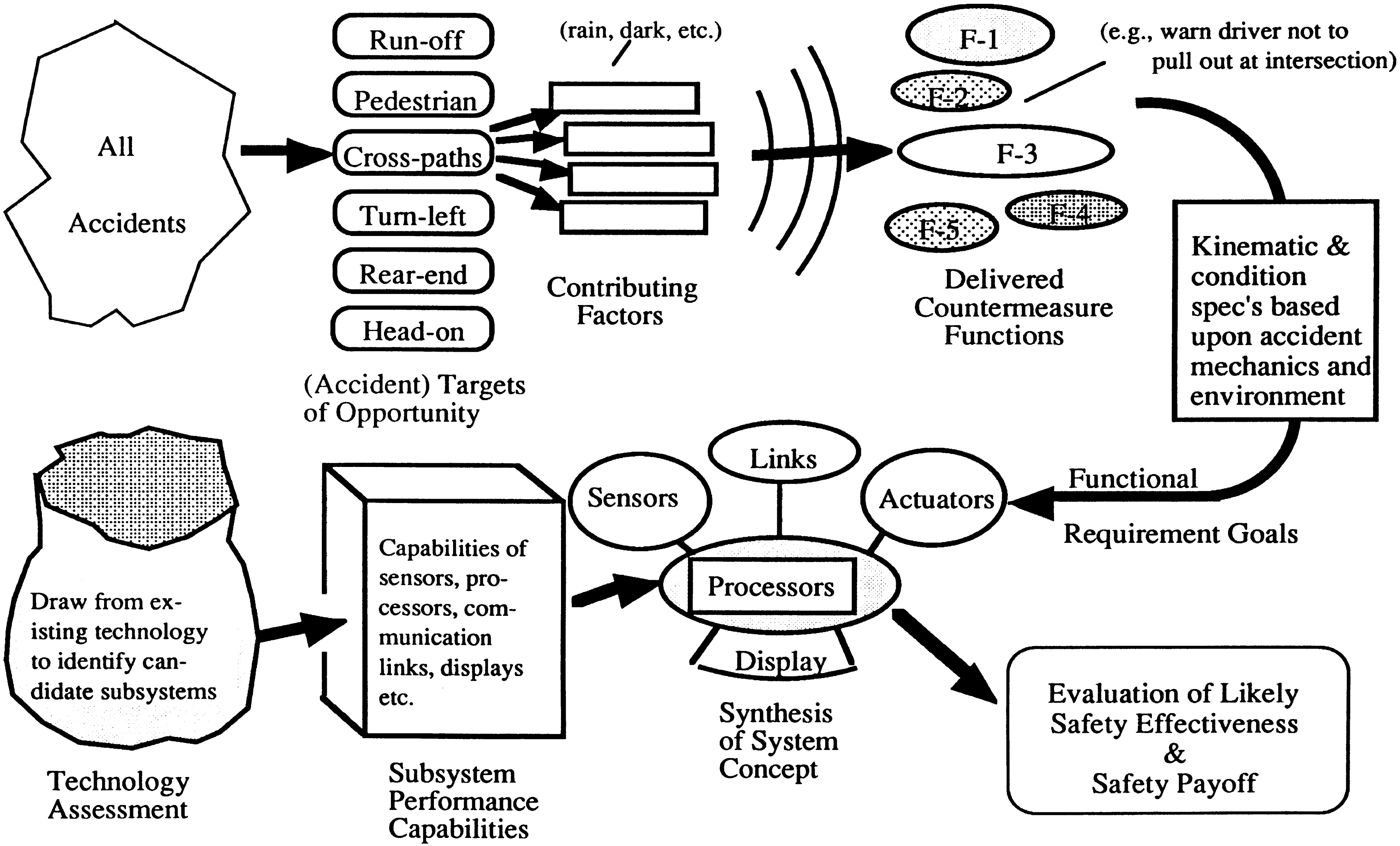


Figure 1. General overview of project methodology.

CHAPTER 3. SELECTION OF TARGET CRASH TYPES

The safe and effective application of advanced technologies to the problem of collision avoidance first requires an understanding of the traffic situations in which collisions occur. Information concerning the precrash scenario, including the relative positions and paths of the involved vehicles and their driving maneuvers, is particularly important. Also necessary is an understanding of the accident environment, such as the lighting and whether the collision took place at an intersection. By classifying accidents in terms of collision avoidance-related factors, targets of opportunity for advanced technology may be assessed. This assessment should include the prevalence of particular collision types, their severity, and their amenability to implementation of countermeasures.

METHODOLOGY

Previous Research

In work sponsored by General Motors and Hughes Aircraft, the University of Michigan Transportation Research Institute (UMTRI) developed a collision typology that classified accidents in terms of the number of vehicles involved, their relative orientation, intent to turn, relation to intersection, and traffic control at the intersection. Distributions of this variable were generated for several factors of interest using data from four computerized files. The distributions proved to be stable from one data set to another. The collision typology was helpful in thinking about crash avoidance technology because it emphasized precrash movements and intents of vehicles. At the same time, the classification scheme was inadequate in some areas. The typology split accidents into those occurring at intersections, at driveways, and on nonjunction sections of roads. A subsequent case review showed the driveway group of accidents to be very diverse. Many of the accidents occurring at driveways had much in common with various types of intersection collisions. Another weakness of the original typology was an overly general treatment of single-vehicle crashes. Therefore, the original collision typology was modified for the present project.

Revision of the collision typology and creation of the analysis file

First, many of the accidents occurring at driveways were redistributed among the appropriate categories of intersection collisions. A residual group of driveway/parking accidents that did not fit any other category was maintained. Since driveways typically have no form of traffic control, this led to the exclusion of the traffic-control variable from the new typology.

Next, the group of single-vehicle accidents was divided into finer categories based on the main harmful event. The categories include striking a pedestrian, pedalcyclist, or animal; overturning; striking a fixed-object; striking a parked vehicle; other; and unknown.

The revised collision typology for two-vehicle accidents contains ten levels. The first six categories describe crashes that took place at an intersection or driveway. They are classified according to whether the vehicles were proceeding on crossing paths prior to the accident, or traveling in the same direction, or approaching from opposite directions. Each of these situations is split according to whether both vehicles were proceeding straight ahead prior to the crash or whether one or both vehicles was attempting a turn. The next pair of categories describes accidents that did not occur at an intersection or driveway. These accidents are divided according to whether the vehicles were approaching in the same direction or from opposite directions. The next category is the parking/driveway group, which includes accidents that occurred when a vehicle was entering or leaving a parking place, as well as driveway accidents, primarily involving a vehicle backing up, that could not be classified in one of the first six categories. Finally, there is a residual other/unknown two-vehicle crash category.

Because of the consistency among different data files observed during the earlier research project, the revised collision typology was run on just one file—NHTSA's CARDfile.[4] The 1984-1986 version of CARDfile was used for the analysis. Given the extremely large size of the file, a specially prepared stratified random sample file was derived for this project. Five percent of the cases at the accident level were drawn from each of the six states in the file for each of the three years. This 5-percent file contains 211,943 accident records and 370,151 vehicle records. The sample file was used to build a file of single-vehicle accidents and a file of two-vehicle accidents. Each record in the two-vehicle file contains all of the accident-level variables, all of the variables describing the first vehicle and driver involved in the accident, and all of the variables for the other involved vehicle and driver. The advantage of working with the two-vehicle file is the detail it provides about the precrash actions of both vehicles involved in an accident. Collisions involving more than two vehicles were not considered in the analysis because information on the precrash collision configuration is not available in CARDfile. The analysis was restricted to collisions involving at least one passenger car or light truck or van. Accounting for these exclusions, the single-vehicle analysis file contains 55,186 records and the two-vehicle file contains 124,329 accident records.

DISTRIBUTIONS BASED ON THE COLLISION TYPOLOGY

Tables 1 and 2 show the distribution of the collision typology categories according to accident severity for single-vehicle and two-vehicle collisions. In this classification, the three most common types of collisions are fixed-object single-vehicle accidents (about 16 percent of the total); two vehicles proceeding straight on crossing legs of an intersection or driveway (12.5 percent); and two vehicles proceeding in the same direction on a nonjunction road segment (11.4 percent). Some of the collision types are associated with a higher degree of severity than others. For example, among the single-vehicle collisions category, rollovers, fixed-object collisions, and pedestrian/bicyclist/animal collisions account for proportionally more of the casualty accidents than the property-damage-only (PDO) accidents. Among the two-vehicle crashes, the same is true for crossing paths/both straight, opposite directions/one or both turning, and opposite directions/nonjunction road section. In figure 2, the sixteen categories of accidents are ordered according to prevalence, with the bars representing frequencies of casualty, PDO, and all accidents.

Table 1. Collision type by injury severity for all crashes (frequencies).

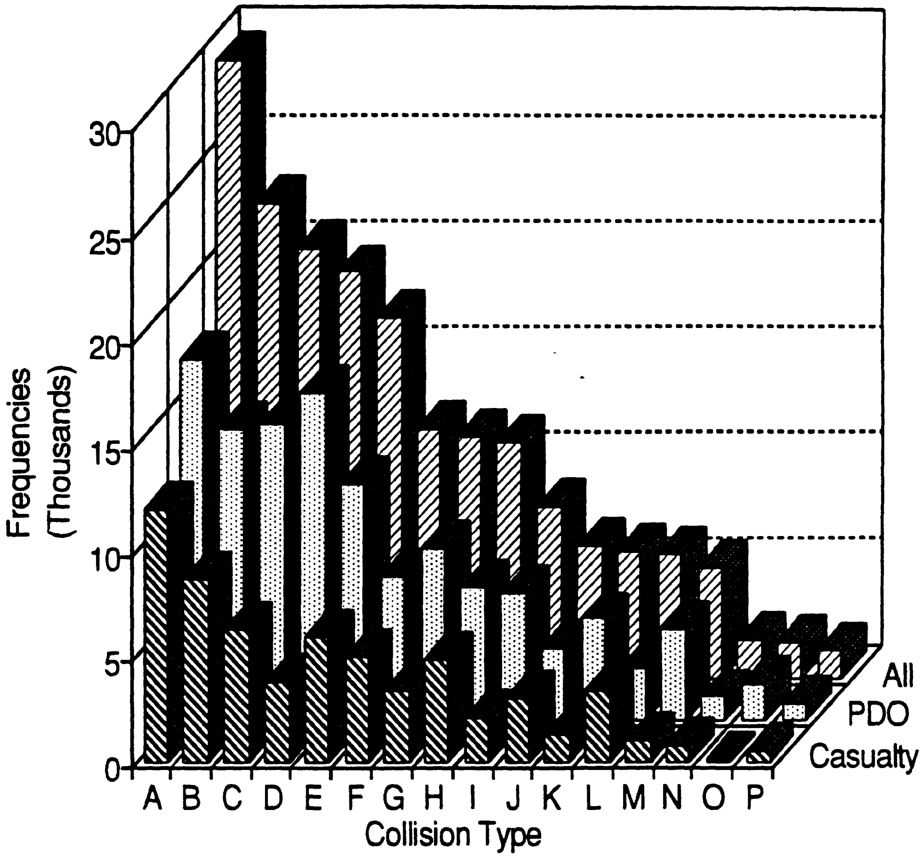
COLLISION TYPE	ACCIDENT SEVERITY PDO	CASUALTY	TOTAL
PED/BIKE/ANIMAL	6,315	4,797	11,112
ROLLOVER	2,483	3,397	5,880
FIXED-OBJECT	17,121	11,910	29,031
PARKED VEHICLE	4,799	1,295	6,097
OTHER SINGLE-VEHICLE	817	453	1,271
UNKNOWN SINGLE-VEHICLE	1,639	116	1,755
INTERSECTION/DRIVEWAY			
CROSSING PATHS			
Straight	13,762	8,711	22,473
Turn	8,122	3,328	11,451
SAME DIRECTION			
Straight	11,225	5,927	17,155
Turn	6,065	2,079	8,145
OPPOSITE DIRECTION			
Straight	1,108	760	1,869
Turn	6,876	4,958	11,835
NONJUNCTION			
SAME DIRECTION	14,116	6,316	20,433
OPPOSITE DIRECTION	3,393	2,956	6,349
PARKING/DRIVEWAY	4,340	985	5,328
OTHER TWO-VEHICLE	15,481	3,810	19,291
TOTAL	117,662	61,798	179,460

Table 2. Collision type by injury severity for all crashes (column percents).

COLLISION TYPE	ACCIDENT SEVERITY PDO	ACCIDENT SEVERITY CASUALTY	TOTAL
PED/BIKE/ANIMAL	5.37	7.76	6.19
ROLLOVER	2.11	5.50	3.28
FIXED-OBJECT	14.55	19.27	16.19
PARKED VEHICLE	4.08	2.10	3.40
OTHER SINGLE-VEHICLE	0.69	0.73	0.71
UNKNOWN SINGLE-VEHICLE	1.39	0.19	0.98
INTERSECTION/DRIVEWAY			
CROSSING PATHS			
Straight	11.70	14.10	12.52
Turn	6.90	5.39	6.38
SAME DIRECTION			
Straight	9.54	9.59	9.56
Turn	5.15	3.36	4.54
OPPOSITE DIRECTION			
Straight	0.94	1.23	1.04
Turn	5.84	8.02	6.59
NONJUNCTION			
SAME DIRECTION	12.00	10.22	11.38
OPPOSITE DIRECTION	2.88	4.78	3.54
PARKING/DRIVEWAY	3.69	1.59	2.97
OTHER TWO-VEHICLE	13.16	6.17	10.75
TOTAL	100.00	100.00	100.00

Two-vehicle collision distributions

Distributions were prepared for the ten classes of two-vehicle accidents according to lighting at the time of the accident and according to land use (rural/urban). In tables 3 and 4 lighting is split into day, dark but lit, dark and unlit, dawn, and dusk. Nearly 75 percent of the collisions occurred during daylight and about 22 percent occurred at night. Some differences are apparent with respect to lighting. For example, both nonjunction collisions with vehicles approaching in the same direction and from opposite directions were more common in a dark, unlit environment than under other lighting conditions.



KEY

A	Fixed Object
B	Intersection/Driveway, Crossing Paths, Straight
C	Nonjunction, Same Direction
D	Other Two-Vehicle
E	Intersection/Driveway, Same Direction, Straight
F	Intersection/Driveway, Opposite Directions, Turning
G	Intersection/Driveway, Crossing Paths, Turning
H	Ped/Bike/Animal
I	Intersection/Driveway, Same Direction, Turning
J	Nonjunction, Opposite Directions
K	Parked Vehicle
L	Rollover
M	Parking/Driveway
N	Intersection/Driveway, Opposite Directions, Straight
O	Unknown Single-Vehicle
P	Other Single-Vehicle

Figure 2. Collision type by injury severity.

Table 3. Collision type by lighting for all two-vehicle crashes (frequencies).

COLLISION TYPE	LIGHTING DAY	DARK/ LIT	DARK/ UNLIT	DAWN	DUSK	TOTAL
INTERSECTIONS						
CROSSING PATHS						
Straight	17,159	2,944	1,589	216	550	22,458
Turn	8,937	1,109	998	125	273	11,442
SAME DIRECTION						
Straight	12,614	2,444	1,486	164	429	17,137
Turn	6,215	908	754	71	193	8,141
OPPOSITE DIRECTION						
Straight	1,182	364	232	24	64	1,866
Turn	8,470	1,888	974	129	367	11,828
NONJUNCTION						
SAME DIRECTION	14,524	2,511	2,549	311	517	20,412
OPPOSITE DIRECTION	4,026	770	1,241	97	208	6,342
PARKING/DRIVEWAY	4,213	596	302	34	156	5,301
OTHER/UNKNOWN	14,147	2,486	1,587	215	574	19,009
TOTAL	91,487	16,020	11,712	1,386	3,331	123,936

Table 4. Collision type by lighting for all two-vehicle crashes (column percents).

COLLISION TYPE	LIGHTING DAY	DARK/ LIT	DARK/ UNLIT	DAWN	DUSK	TOTAL
INTERSECTIONS						
CROSSING PATHS						
Straight	18.76	18.38	13.57	15.58	16.51	18.12
Turn	9.77	6.92	8.52	9.02	8.20	9.23
SAME DIRECTION						
Straight	13.79	15.26	12.69	11.83	12.88	13.83
Turn	6.79	5.67	6.44	5.12	5.79	6.57
OPPOSITE DIRECTION						
Straight	1.29	2.27	1.98	1.73	1.92	1.51
Turn	9.26	11.79	8.32	9.31	11.02	9.54
NONJUNCTION						
SAME DIRECTION	15.88	15.67	21.76	22.44	15.52	16.47
OPPOSITE DIRECTION	4.40	4.81	10.60	7.00	6.24	5.12
PARKING/DRIVEWAY	4.61	3.72	2.58	2.45	4.68	4.28
OTHER/UNKNOWN	15.46	15.52	13.55	15.51	17.23	15.34
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00

Tables 5 and 6 list the two-vehicle collision typology according to urban versus rural area. Many of the differences between the distributions are not surprising. Parking/driveway collisions were more common in urban areas, while both of the nonjunction categories were overrepresented in rural areas. Several of the intersection/driveway categories showed little difference with respect to land use, while crossing paths/both straight, same direction/both straight, and opposite directions/one or both turning were all more common in urban areas than rural areas.

Table 5. Collision type by land use for all two-vehicle crashes (frequencies).

COLLISION TYPE	LAND USE URBAN	RURAL	TOTAL
INTERSECTIONS			
CROSSING PATHS			
Straight	9,565	2,090	11,655
Turn	2,971	981	3,952
SAME DIRECTION			
Straight	8,354	1,646	10,000
Turn	2,735	778	3,513
OPPOSITE DIRECTION			
Straight	893	364	1,257
Turn	4,487	986	5,473
NONJUNCTION			
SAME DIRECTION	8,588	4,081	12,669
OPPOSITE DIRECTION	1,706	1,846	3,552
PARKING/DRIVEWAY	3,076	475	3,551
OTHER/UNKNOWN	11,214	3,489	14,703
TOTAL	53,589	16,736	70,325

Table 6. Collision type by land use for all two-vehicle crashes (column percents).

COLLISION TYPE	LAND USE URBAN	RURAL	TOTAL
INTERSECTIONS			
CROSSING PATHS			
Straight	17.85	12.49	16.57
Turn	5.54	5.86	5.62
SAME DIRECTION			
Straight	15.59	9.84	14.22
Turn	5.10	4.65	5.00
OPPOSITE DIRECTION			
Straight	1.67	2.17	1.79
Turn	8.37	5.89	7.78
NONJUNCTION			
SAME DIRECTION	16.03	24.38	18.01
OPPOSITE DIRECTION	3.18	11.03	5.05
PARKING/DRIVEWAY	5.74	2.84	5.05
OTHER/UNKNOWN	20.93	20.85	20.91
TOTAL	100.00	100.00	100.00

Distributions of the two-vehicle collisions were also prepared for the original CARDfile accident-type variable. This variable is useful for its detail on vehicle movements. Table 7 lists the frequencies and percentages of each of the levels of this variable for two-vehicle collisions. Subtotals for each major category are printed in boldface.

Table 7. CARDfile collision type distribution.

	Frequency	Percent
REAR-END, SAME TRAFFICWAY, SAME DIRECTION	**38,804**	**31.21**
Lead vehicle stopped	18,060	14.53
Lead vehicle moving straight	9,059	7.29
Lead vehicle turning	8,246	6.63
Specifics unknown	3,439	2.77
SIDESWIPE, SAME TRAFFICWAY, SAME DIRECTION	**7,019**	**5.65**
Passing	2,450	1.97
Overtaking on the right	143	0.12
Overtaking on the left	331	0.27
Changing lanes	2,273	1.83
Specifics unknown	1,822	1.47
OTHER SAME TRAFFICWAY, SAME DIRECTION	**963**	**0.77**

Table 7. CARDfile collision type distribution (continued).

HEAD-ON SIDESWIPE, SAME TRAFFICWAY, OPPOSITE DIRECTION	**7,048**	**5.67**
Lateral move/lane change	335	0.27
Both straight/passing	4,965	3.99
Specifics unknown	1,748	1.41
OTHER SAME TRAFFICWAY, OPPOSITE DIRECTION	**239**	**0.19**
INITIAL OPPOSITE DIRECTIONS, CHANGE TRAFFICWAY/TURN ACROSS PATH	**12,775**	**10.28**
One vehicle straight/stopped, one turning right	36	0.03
One vehicle straight/stopped, one turning left	12,140	9.76
One turning left, one turning right	183	0.15
Both turning left	131	0.11
Specifics unknown	285	0.23
INITIAL SAME DIRECTION, CHANGE TRAFFICWAY/TURN ACROSS PATH	**1,653**	**1.33**
One vehicle straight/stopped, one turning right	539	0.43
One vehicle straight/stopped, one turning left	707	0.57
Both vehicles change trafficway	407	0.33
INTERSECTING PATHS/ANGLES	**38,357**	**30.85**
Both straight	23,359	18.79
Both curving/turning	644	0.52
Resulting same direction, left turning vehicle	2,100	1.69
Resulting same direction, right turning vehicle	1,926	1.55
Resulting opposite direction, left turning vehicle	5,272	4.24
Resulting opposite direction, right turning vehicle	879	0.71
Resulting direction unknown, specifics unknown, turning	2,470	1.99
Other intersecting paths/angles	1,707	1.37
BACKING	**6,278**	**5.05**
One vehicle backing	6,022	4.84
Two vehicles backing	256	0.21
ENTER/LEAVE PARKING SPACE	**1,999**	**1.61**
OTHER COLLISION INVOLVING TWO VEHICLES	**9,194**	**7.39**
TOTAL	**124,329**	**100.00**

Single-vehicle collision distributions

Distributions were prepared for the six categories of single-vehicle accidents according to several factors of interest, including lighting, weather condition, road surface condition, land use, driver age, driver gender, and alcohol/drug use. This set of distributions (table 8) clearly illustrates that single-vehicle accidents are a diverse group, with different factors associated with particular types of accidents. For example, young drivers between the ages of 16 and 25 years of age accounted for about half of rollover and fixed-object collisions but less than 30 percent of pedestrian/bicyclist/animal accidents. Some of the differences are intuitive, such as 72 percent of parked vehicle accidents occurring in urban areas.

One other aspect of single-vehicle accidents examined was the primary impact location (tables 9 and 10): on the roadway, on the shoulder, or off the roadway. The single-vehicle collisions were divided more finely for this analysis. Pedestrian/bicyclist accidents were examined separately from collisions with an animal, and noncollisions were removed from the "other" group to form their own category. Examples of noncollisions are fire, mechanical failure, and falling from the vehicle. The remaining "other" cases include accidents that do not fit any of the other categories, such as collisions with trains and animal-drawn vehicles.

The table 8 distributions indicated many similarities between rollovers and fixed-object collisions. One reason for this may be their similarity in terms of primary impact location. As table 10 shows, about 70 percent of both rollovers and fixed-object collisions took place off the roadway. In both types of collisions, the vehicle often leaves the road and whether it strikes a fixed-object or overturns probably depends largely on the roadway environment. In sharp contrast, about 95 percent of pedestrian/bicyclist collisions and 99 percent of animal collisions occurred on the roadway. These cases are likely to involve some element of surprise, with the unexpected appearance of the person or animal on the roadway contributing to the crash. Differences such as these have important implications for the implementation of advanced collision avoidance technology.

Table 8. Factors of interest for single-vehicle accidents.

LIGHT CONDITION

	PED/BIKE/ANIMAL		ROLLOVER		FIXED OBJECT		PARKED VEHICLE		OTHER S.V.		UNKNOWN S.V.		TOTAL	
UNKNOWN	18	0.16	7	0.12	68	0.23	33	0.54	3	0.24	53	3.02	182	0.33
DAY	4,676	42.08	2,420	41.12	11,520	39.63	2,716	44.55	677	53.27	1,008	57.44	23,017	41.71
DARK/LIT	887	7.98	463	7.87	5,817	20.01	2,233	36.62	174	13.69	230	13.11	9,804	17.77
DARK/NOT LIT	4,703	42.32	2,730	46.39	10,397	35.77	870	14.27	362	28.48	392	22.34	19,454	35.25
DAWN	413	3.72	135	2.29	630	2.17	86	1.41	12	0.94	20	1.14	1,296	2.35
DUSK	415	3.73	130	2.21	634	2.18	159	2.61	43	3.38	52	2.96	1,433	2.60
TOTAL	11,112	100.00	5,885	100.00	29,066	100.00	6,097	100.00	1,271	100.00	1,755	100.00	55,186	100.00

WEATHER CONDITION

	PED/BIKE/ANIMAL		ROLLOVER		FIXED OBJECT		PARKED VEHICLE		OTHER S.V.		UNKNOWN S.V.		TOTAL	
UNKNOWN	26	0.23	7	0.12	69	0.24	46	0.75	4	0.31	60	3.42	212	0.38
CLEAR	9,724	87.51	4,572	77.69	21,394	73.60	4,848	79.51	1,065	83.79	1,464	83.42	43,067	78.04
RAIN	876	7.88	716	12.17	4,631	15.93	726	11.91	132	10.39	154	8.77	7,235	13.11
SNOW/ICE	264	2.38	429	7.29	2,272	7.82	403	6.61	52	4.09	64	3.65	3,484	6.31
OTHER	222	2.00	161	2.74	700	2.41	74	1.21	18	1.42	13	0.74	1,188	2.15
TOTAL	11,112	100.00	5,885	100.00	29,066	100.00	6,097	100.00	1,271	100.00	1,755	100.00	55,186	100.00

ROAD SURFACE CONDITION

	PED/BIKE/ANIMAL		ROLLOVER		FIXED OBJECT		PARKED VEHICLE		OTHER S.V.		UNKNOWN S.V.		TOTAL	
UNKNOWN	65	0.58	34	0.58	142	0.49	54	0.89	10	0.79	63	3.59	368	0.67
DRY	8,942	80.47	3,712	63.08	17,208	59.20	3,979	65.26	941	74.04	1,242	70.77	36,024	65.28
WET	1,595	14.35	1,048	17.81	6,846	23.55	1,138	18.66	214	16.84	283	16.13	11,124	20.16
SNOW/ICE	504	4.54	1,066	18.11	4,740	16.31	912	14.96	101	7.95	161	9.17	7,484	13.56
OTHER	6	0.05	25	0.42	130	0.45	14	0.23	5	0.39	6	0.34	186	0.34
TOTAL	11,112	100.00	5,885	100.00	29,066	100.00	6,097	100.00	1,271	100.00	1,755	100.00	55,186	100.00

LAND USE

	PED/BIKE/ANIMAL		ROLLOVER		FIXED OBJECT		PARKED VEHICLE		OTHER S.V.		UNKNOWN S.V.		TOTAL	
MISSING	3,068	27.61	2,815	47.83	12,722	43.77	1,054	17.29	516	40.60	199	11.34	20,374	36.92
URBAN	2,509	22.58	612	10.40	7,303	25.13	4,387	71.95	352	27.69	1,128	64.27	16,291	29.52
RURAL	5,535	49.81	2,458	41.77	9,041	31.11	656	10.76	403	31.71	428	24.39	18,521	33.56
TOTAL	11,112	100.00	5,885	100.00	29,066	100.00	6,097	100.00	1,271	100.00	1,755	100.00	55,186	100.00

LAND USE/LIGHT CONDITION

	PED/BIKE/ANIMAL		ROLLOVER		FIXED OBJECT		PARKED VEHICLE		OTHER S.V.		UNKNOWN S.V.		TOTAL	
URB/DAY	1,714	15.42	254	4.32	2,888	9.94	2,027	33.25	181	14.24	715	40.74	7,779	14.10
URB/DARK	785	7.06	356	6.05	4,381	15.07	2,327	38.17	171	13.45	384	21.88	8,404	15.23
RUR/DAY	1,288	11.59	1,059	17.99	3,806	13.09	306	5.02	199	15.66	211	12.02	6,869	12.45
RUR/DARK	4,239	38.15	1,394	23.69	5,203	17.90	350	5.74	202	15.89	193	11.00	11,581	20.99
MISS/UNK	3,086	27.77	2,822	47.95	12,788	44.00	1,087	17.83	518	40.76	252	14.36	20,553	37.24
TOTAL	11,112	100.00	5,885	100.00	29,066	100.00	6,097	100.00	1,271	100.00	1,755	100.00	55,186	100.00

Table 8. Factors of interest for single-vehicle accidents (continued).

DRIVER AGE

	PED/BIKE/ANIMAL		ROLLOVER		FIXED OBJECT		PARKED VEHICLE		OTHER S.V.		UNKNOWN S.V.		TOTAL	
< 16	14	0.13	48	0.82	234	0.81	50	0.82	1	0.08	11	0.63	358	0.65
16-25	3,186	28.67	3,057	51.95	14,139	48.64	2,092	34.31	469	36.90	598	34.07	23,541	42.66
26-55	5,880	52.92	2,355	40.02	11,164	38.41	1,977	32.43	647	50.90	748	42.62	22,771	41.26
56+	1,456	13.10	260	4.42	1,871	6.44	587	9.63	114	8.97	248	14.13	4,536	8.22
MISS/UNK	576	5.18	165	2.80	1,658	5.70	1,391	22.81	40	3.15	150	8.55	3,980	7.21
TOTAL	11,112	100.00	5,885	100.00	29,066	100.00	6,097	100.00	1,271	100.00	1,755	100.00	55,186	100.00

DRIVER GENDER

	PED/BIKE/ANIMAL		ROLLOVER		FIXED OBJECT		PARKED VEHICLE		OTHER S.V.		UNKNOWN S.V.		TOTAL	
MISSING	43	0.39	11	0.19	153	0.53	200	3.28	2	0.16	5	0.28	414	0.75
UNKNOWN	216	1.94	88	1.50	894	3.08	290	4.76	19	1.49	15	0.85	1,522	2.76
FEMALE	3,361	30.25	1,572	26.71	8,349	28.72	1,711	28.06	363	28.56	614	34.99	15,970	28.94
MALE	7,486	67.37	4,209	71.52	19,594	67.41	3,798	62.29	882	69.39	1,116	63.59	37,085	67.20
NDR	6	0.05	5	0.08	76	0.26	98	1.61	5	0.39	5	0.28	195	0.35
TOTAL	11,112	100.00	5,885	100.00	29,066	100.00	6,097	100.00	1,271	100.00	1,755	100.00	55,186	100.00

ALCOHOL/DRUG USE

	PED/BIKE/ANIMAL		ROLLOVER		FIXED OBJECT		PARKED VEHICLE		OTHER S.V.		UNKNOWN S.V.		TOTAL	
UNKNOWN	466	4.19	171	2.91	1,509	5.19	1,226	20.11	54	4.25	208	11.85	3,634	6.59
NONE	10,356	93.20	4,204	71.44	20,165	69.38	3,459	56.73	1,088	85.60	1,438	81.94	40,710	73.77
ALCOHOL	280	2.52	1,494	25.39	7,189	24.73	1,303	21.37	123	9.68	102	5.81	10,491	19.01
DRUGS	4	0.04	11	0.19	127	0.44	11	0.18	1	0.08	2	0.11	156	0.28
NDR	6	0.05	5	0.08	76	0.26	98	1.61	5	0.39	5	0.28	195	0.35
TOTAL	11,112	100.00	5,885	100.00	29,066	100.00	6,097	100.00	1,271	100.00	1,755	100.00	55,186	100.00

Table 9. Single-vehicle collisions by primary impact location (frequencies).

COLLISION TYPE	PRIMARY IMPACT LOCATION On Roadway	On Shoulder	Off Roadway	Unknown	TOTAL
Rollover	904	829	4,147	5	5,885
Fixed-object	2,283	6,598	20,163	22	29,066
Ped/Bike	4,735	106	167	4	5,012
Animal	5,877	8	32	8	5,925
Parked Vehicle	2,828	333	2,914	22	6,097
Noncollision	554	84	165	1	804
Specifics Unk	707	36	1,131	56	1,930
Other	429	2	35	1	467
TOTAL	18,317	7,996	28,754	119	55,186

Table 10. Single-vehicle collisions by primary impact location (percents).

COLLISION TYPE	PRIMARY IMPACT LOCATION On Roadway	On Shoulder	Off Roadway	Unknown	TOTAL
Rollover	15.36	14.09	70.47	0.08	100.00
Fixed-object	7.85	22.70	69.37	0.08	100.00
Ped/Bike	94.47	2.11	3.33	0.08	100.00
Animal	99.19	0.14	0.54	0.14	100.01
Parked Vehicle	46.38	5.46	47.79	0.36	100.00
Noncollision	68.91	10.45	20.52	0.12	100.00
Specifics Unk	36.63	1.87	58.60	2.90	100.00
Other	91.86	0.43	7.49	0.21	100.00
TOTAL	33.19	14.49	52.10	0.22	100.00

TARGET COLLISION TYPES

Based on the CARDfile analyses, six collision types were selected as targets for the application of advanced technology to improve safety. The six types include two single-vehicle collision types and four two-vehicle types:

- Run-off-road collisions (single vehicle strikes a fixed-object or overturns off the roadway).
- Single vehicle strikes pedestrian, cyclist, or animal.
- Crossing paths at intersection or driveway (two vehicles, both straight).
- Left turn collisions (one vehicle turns left across path of another, at intersection or driveway).
- Rear-end collisions between two vehicles moving in same direction.
- Head-on collisions between two vehicles approaching from opposite directions.

The six collision types selected account for 68 percent of all single-vehicle and two-vehicle accidents analyzed (table 11). The two single-vehicle categories comprise 78 percent of all the single-vehicle accidents, while the four two-vehicle categories represent 64 percent of all two-vehicle collisions. Because of the prevalence of these kinds of collisions, there is a high potential for reduction in the number of accidents through the implementation of advanced technology. One of the collision types selected—head-on crashes—represents only 4 percent of all accidents but was chosen because of its relatively high probability of injury.

Table 11. Proportion of selected collision types out of all single-vehicle and two-vehicle collisions (based on 1984-1986 CARDfile).

COLLISION TYPE	N	Percentage of 1 Vehicle	Percentage of 2 Vehicles	% of both
Run-off road	31,737	57.5	--	17.7
Ped/Bike/Animal	11,112	20.1	--	6.2
Crossing paths	22,473	--	18.1	12.5
Left turn	11,318	--	9.1	6.3
Rear-end	38,804	--	31.2	21.6
Head-on	7,048	--	5.7	3.9
TOTAL	122,492	77.6	64.1	68.2

Associated factors and countermeasures

Designing countermeasures for specific crash types requires knowledge not just of the collision geometry but also of factors associated with the crash type. For example, a large percentage of some types of crashes takes place at night. A technology that somehow improves night vision could potentially prevent many of these crashes. Other types of crashes only rarely occur at night, so the same technology probably would not be effective in reducing those crashes. In the present study, certain countermeasure functions (CF's) were proposed for each of the six selected collision types. Then additional analyses were conducted using CARDfile data to estimate the proportion of each collision type that could potentially be addressed by specific CF's.

Run-off-road (ROR) crashes

Six main CF's were proposed for crashes where a single vehicle overturns or strikes a fixed-object off the roadway (including the road shoulder):

- Lane-edge detection (addresses *all* ROR crashes).
- Friction detection (addresses ROR crashes aggravated by excessive speed under low-friction conditions).

- Driver impairment warning (addresses ROR crashes aggravated by alcohol/drug impairment).
- Nighttime vision enhancement (addresses ROR crashes aggravated by dark, unlit. conditions).
- Fog detection (addresses ROR crashes aggravated by sudden encounter with fog patch).
- Ice detection (addresses ROR crashes aggravated by sudden encounter with snow/ice patch).

To estimate the proportion of ROR collisions that could possibly be affected by each proposed CF, the ROR crashes were broken down according to relevant associated factors. Lane-edge detection, proposed as applicable to *all* ROR crashes, was not considered. Collisions involving a speeding driver on a wet, snowy, or icy roadway were candidates for friction detection. If alcohol or drug use was indicated for the driver, the collision was considered applicable to driver-impairment warnings. Crashes coded dark/unlit under lighting were relevant to nighttime vision enhancement, and collisions on a snowy/icy roadway were possibilities for ice-detection countermeasures. Accidents appropriate for fog detection CF's were not identified because the CARDfile weather conditions variable does not include fog as a separate level.

Table 12 (and the subsequent tables) present the data in two forms. At the bottom of table 12 are the total number and percentage of ROR crashes involving each associated factor. The categories overlap each other since some accidents involve more than one factor. The factors include: (1) an alcohol- or drug-involved driver, (2) dark and unlit conditions, (3) snowy or icy roadway, and (4) excessive speed under low-friction conditions (wet *or* snowy/icy roadway). The percentage of ROR crashes involving any given factor may be taken to indicate the absolute *maximum* percentage that could benefit from the respective CF.

The top portion of table 12 indicates all of the combinations of the associated factors. Here the data are presented in mutually exclusive categories. In the original list of CF's, the friction-detection and ice-detection categories overlap each other. Accidents involving a speeding driver on a snowy/icy roadway pertain to both groups. Therefore, in the top of table 12, the cases were split into snowy/icy roads where the driver was not speeding; snowy/icy roads with a speeding driver; and wet roads with a speeding driver. The first two are relevant to ice detection, and the latter two apply to friction detection. The frequency and percentage of ROR crashes involving only one factor are indicated as are all combinations of the factors.

Table 12. Run-off-road crashes.

N=31,737 — 57.5 percent of all single-vehicle accidents
17.7 percent of all single-vehicle and two-vehicle accidents

	Frequency	Percent
Alcohol/drugs only	3,261	10.28
Dark, unlit only	5,416	17.07
Snowy/icy roads only (no speed)	1,974	6.22
Snowy/icy roads and speed-related	1,299	4.09
Wet and speed-related	1,586	5.00
Alcohol and dark only	3,831	12.07
Alcohol and snow/ice only (no speed)	116	0.37
Alcohol and snow/ice and speed-related	73	0.23
Alcohol and wet and speed-related	246	0.78
Dark and snow/ice only (no speed)	935	2.95
Dark and snow/ice and speed-related	700	2.21
Dark and wet and speed-related	768	2.42
Alcohol, dark, and snow/ice (no speed)	183	0.58
Alcohol, dark, snow/ice, and speed-related	158	0.50
Alcohol, dark, wet, and speed-related	302	0.95
None of the above	10,889	34.31
	31,737	100.00
Total alcohol/drugs	8,170	25.76
Total dark, unlit	12,293	38.75
Total snow/ice	5,438	17.15
Total excessive speed under low-friction	5132.00	16.18

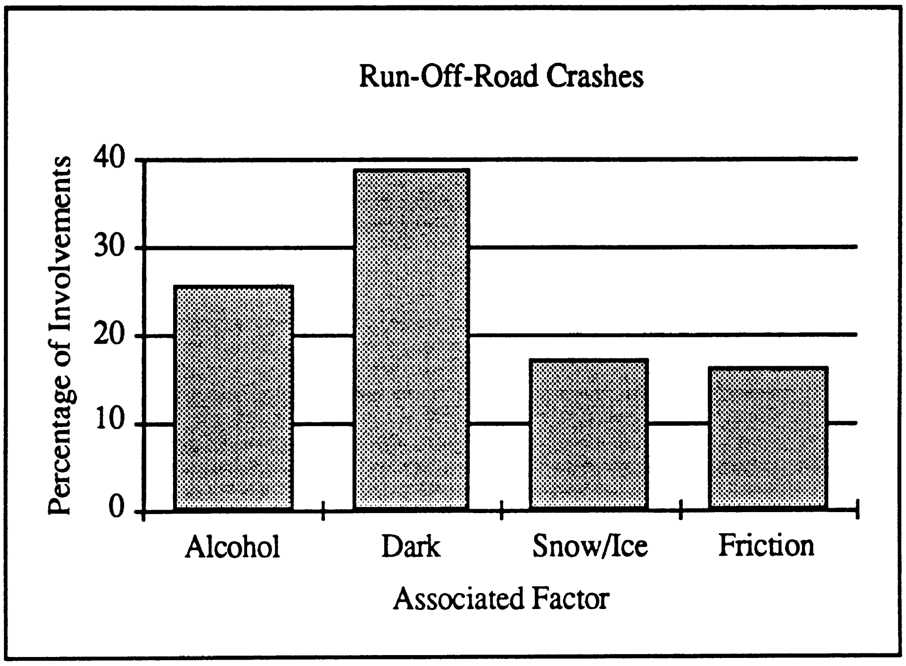


Figure 3. Associated factors of run-off-road crashes.

It is important to remember that these analyses are based on a large, computerized data file. It is only possible to identify *associated* factors, not *contributing* factors. Just because an accident took place on a snowy roadway does not necessarily mean that the roadway surface precipitated the collision. Furthermore, even if a factor did contribute to the crash, there is no guarantee that a CF aimed toward that factor would prevent the collision or mitigate its severity.

With this in mind, it is possible to make some generalizations about the ROR crashes. About 39 percent took place under dark, unlit conditions; 26 percent involved an impaired driver; 17 percent occurred on a snowy/icy roadway; and 16 percent involved a speeding driver on a wet or snowy/icy roadway (figure 3). Only 34 percent of the crashes did not involve any of these factors. The combinations of factors shown in the top of Table 12 indicate instances where more than one CF is necessary or at least where a particular function will have to perform under additional constraints. For example, 14 percent of the ROR crashes involved an impaired driver *and* dark, unlit conditions (and in some cases a poor roadway surface as well). This represents over half of all the alcohol-involved crashes and over one-third of all the dark, unlit involvements.

Vehicle strikes pedestrian/cyclist/animal

The next collision type includes accidents where a single vehicle strikes a pedestrian, pedalcyclist, or animal. The proposed CF's include three of the ones evaluated for ROR crashes: driver impairment warning, nighttime vision enhancement, and ice detection. Appropriate crashes were identified respectively as those involving a drug- or alcohol-involved driver, occurring under dark and unlit conditions, and taking place on a snowy or icy roadway.

The percentage of pedestrian/cyclist/animal (PCA) collisions taking place under dark/unlit conditions (42 percent) is slightly higher than the percentage for ROR crashes (39 percent). However, only 2.6 percent of the PCA crashes involved alcohol (table 13), compared with 25.8 percent of the ROR crashes, and only 4.5 percent of the PCA crashes took place on snowy/icy roadways, compared with 17.1 percent of the ROR collisions. These clearly are two very different types of collisions. One seems to involve a driver losing control of the vehicle, frequently in conjunction with an impaired condition and/or a snowy or icy road surface. In the other, the driver is in full control of the vehicle but suddenly encounters an object on the roadway. The two collision types share the feature of a high proportion of dark, unlit conditions, but other than this, it seems that different countermeasure strategies would have to be employed to prevent them.

Table 13. Vehicle strikes pedestrian/cyclist/animal.

N=11,112 — 20.1 percent of all single-vehicle accidents
6.2 percent of all single-vehicle and two-vehicle accidents

	Frequency	Percent
Alcohol/drugs only	146	1.31
Dark, unlit only	4,247	38.22
Snowy/icy roads only	166	1.49
Alcohol and dark only	124	1.12
Alcohol and snow/ice only	6	0.05
Dark and snow/ice only	324	2.92
Alcohol, dark, and snow/ice	8	0.07
None of the above	6,091	54.81
	11,112	100.00
Total alcohol/drugs	284	2.55
Total snow/ice	504	4.53
Total dark, unlit	4,703	42.33

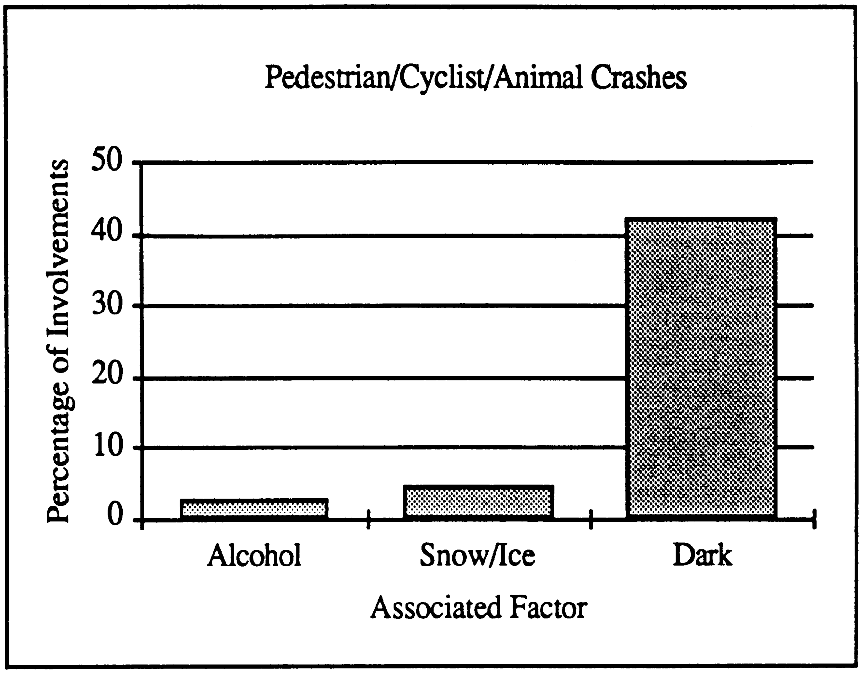


Figure 4. Associated factors of the pedestrian/cyclist/animal crashes.

Crossing paths at intersection, both straight

The next target accident type involves two vehicles approaching on crossing paths at an intersection or driveway, both moving straight. The same three CF's considered for PCA collisions are also suggested for the crossing- paths accidents. In addition, two other suggested CF's are warnings of a vehicle violating a signalized or a signed right-of-way. These were considered relevant to collisions taking place at signalized and signed intersections, respectively.

In contrast to the two single-vehicle accident types considered earlier, only 7 percent of the crossing-paths collisions took place under dark, unlit conditions (table 14). Only 5 percent of the crashes involved at least one impaired driver, and only 6 percent took place on snowy/icy roadways. About 35 percent took place at a signed intersection and 46 percent at a signalized intersection. Thus, countermeasures that warn of impending right-of-way violations should have a better chance of success than other proposed countermeasures for crossing-paths collisions.

Left turn into another's path

The fourth collision type considered involves one vehicle turning left across another vehicle's path, at an intersection or driveway. The same CF's suggested for crossing-paths accidents were considered for this collision group. Comparing the left-turn group with the crossing-paths group, the percentage of collisions involving at least one impaired driver is about the same in both: 5.6 percent for the left turns and 5.1 percent for the crossing paths (table 15). The left turn group has a lower percentage of snowy/icy road involvements (2.5 percent to 5.7 percent) and a slightly higher percentage of dark/unlit involvements (8.3 percent to 7.1 percent). The primary difference between the two groups, in terms of the factors examined, is in the traffic control. Whereas signed intersections were more common for the crossing paths group, signalized intersections were about six times as common as signed intersections for the left-turn group.

Table 14. Crossing paths at intersection, both straight.

N = 22,473 — 18.1 percent of all two-vehicle accidents; 12.5 percent of all single-vehicle and two-vehicle accidents

	Frequency	Percent
Alcohol/drugs only	134	0.60
Dark, unlit only	201	0.89
Snowy/icy roads only (no speed)	268	1.19
Signalized intersection only	6,593	29.34
Signed intersection only	8,570	38.13
Alcohol and dark only	25	0.11
Alcohol and snow/ice only	6	0.03
Dark and snow/ice only	18	0.08
Alcohol and signalized only	379	1.69
Alcohol and signed only	340	1.51
Dark and signalized only	460	2.05
Dark and signed only	562	2.50
Snow/ice and signalized only	229	1.02
Snow/ice and signed only	633	2.82
Alcohol and dark and signalized only	106	0.47
Alcohol and dark and signed only	110	0.49
Snow/ice and dark and signalized only	35	0.16
Snow/ice and dark and signed only	60	0.27
Alcohol and signalized and snow/ice only	17	0.08
Alcohol and signed and snow/ice only	10	0.04
Alcohol and dark and snow/ice only	4	0.02
Alcohol and dark and snow and signalized	5	0.02
Alcohol and dark and snow and signed	3	0.01
None of the above	3,705	16.49
	22,473	100.00
Total alcohol/drugs	1,139	5.07
Total snow/ice	1,288	5.74
Total dark, unlit	1,589	7.07
Total signalized intersection	7,824	34.83
Total signed intersection	10,288	45.77

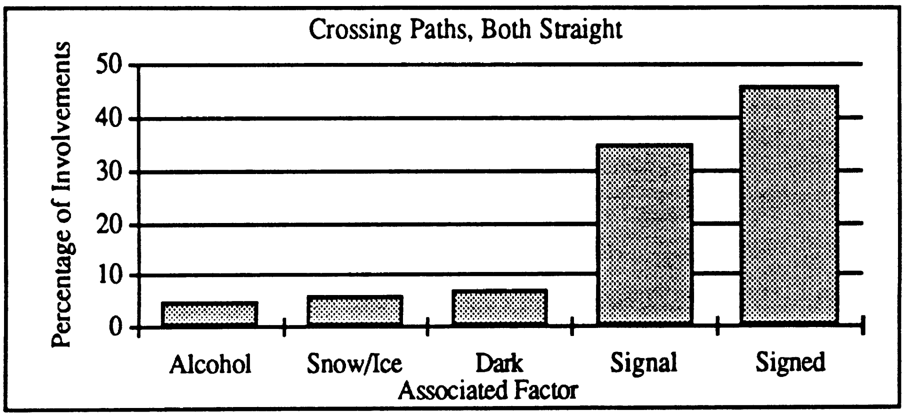


Figure 5. Associated factors of crossing paths collisions.

Table 15. Left turn into another's path.

N = 11,318 9.1 percent of all two-vehicle accidents
6.3 percent of all single-vehicle and two-vehicle accidents

	Frequency	Percent
Alcohol/drugs only	208	1.84
Dark, unlit only	303	2.68
Snowy/icy roads only (no speed)	107	0.95
Signalized intersection only	4,768	42.13
Signed intersection only	782	6.91
Alcohol and dark only	77	0.68
Alcohol and snow/ice only	4	0.04
Dark and snow/ice only	13	0.11
Alcohol and signalized only	222	1.96
Alcohol and signed only	41	0.36
Dark and signalized only	387	3.42
Dark and signed only	61	0.54
Snow/ice and signalized only	97	0.86
Snow/ice and signed only	28	0.25
Alcohol and dark and signalized only	58	0.51
Alcohol and dark and signed only	14	0.12
Snow/ice and dark and signalized only	12	0.11
Snow/ice and dark and signed only	8	0.07
Alcohol and signalized and snow/ice only	7	0.06
Alcohol and signed and snow/ice only	1	0.01
Alcohol and dark and snow/ice only	1	0.01
Alcohol and dark and snow and signalized	3	0.03
Alcohol and dark and snow and signed	0	0.00
None of the above	4,116	36.37
	11,318	100.00
Total alcohol/drugs	636	5.62
Total snow/ice	281	2.50
Total dark, unlit	937	8.28
Total signalized intersection	5,554	49.08
Total signed intersection	935	8.26

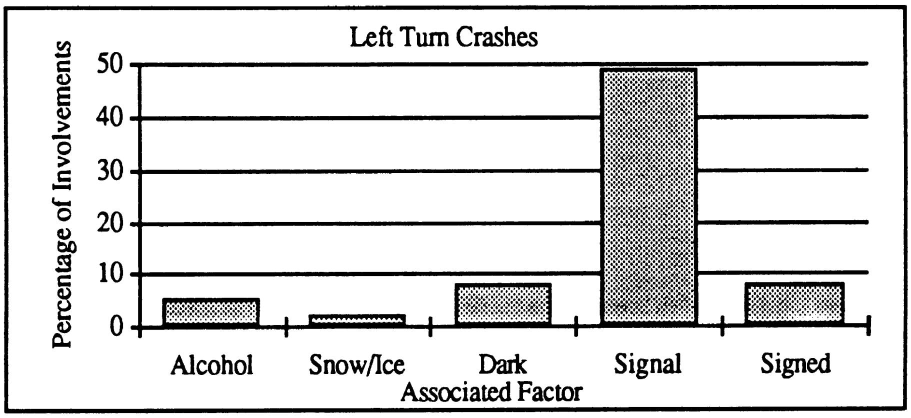


Figure 6. Associated factors of left turn collisions.

Rear-end collisions

The next target collision type involves two vehicles traveling on the same trafficway in the same direction, with the following vehicle striking the rear of the lead vehicle. The CF's considered for this group are the same four considered for the ROR crashes. The analyses suggest a low level of potential for these CF's in preventing rear-end collisions (table 16). Impaired drivers were involved in 6.7 percent of the accidents; dark/unlit conditions characterized 10.4 percent; snowy/icy roads were involved in 6.5 percent; and excessive speed under low-friction (wet or snowy or icy roads) was found in 7.5 percent. About 75 percent of the collisions involved none of these factors.

Head-on collisions

The final collision type involves two vehicles traveling in opposite directions on the same trafficway and colliding head-on. The same four CF's evaluated for rear-end collisions were considered for head-on crashes. There is more potential for these CF's with respect to head-on collisions than for rear-end crashes (table 17). About 15 percent of the head-on's involved at least one impaired driver, 19 percent occurred under dark/unlit conditions, 21 percent took place on snowy/icy roads, and almost 10 percent were characterized by excessive speed under low-friction conditions. About 50 percent of the accidents involved none of these factors.

Table 16. Rear-end collisions.

N = 38,804	31.2 percent of all two-vehicle accidents	
	21.6 percent of all single-vehicle and two-vehicle accidents	
	Frequency	Percent
Alcohol/drugs only	1,677	4.32
Dark, unlit only	2,684	6.92
Snowy/icy roads only (no speed)	1,658	4.27
Snowy/icy roads and speed-related	410	1.06
Wet and speed-related	2,032	5.24
Alcohol and dark only	678	1.75
Alcohol and snow/ice only (no speed)	54	0.14
Alcohol and snow/ice and speed-related	16	0.04
Alcohol and wet and speed-related	85	0.22
Dark and snow/ice only (no speed)	265	0.68
Dark and snow/ice and speed-related	87	0.22
Dark and wet and speed-related	232	0.60
Alcohol and dark and snow/ice (no speed)	25	0.06
Alcohol, dark, snow/ice, and speed-related	14	0.04
Alcohol, dark, wet and speed-related	43	0.11
None of the above	28,844	74.33
	38,804	100.00
Total alcohol/drugs	2,592	6.68
Total dark, unlit	4,028	10.38
Total snow/ice	2,529	6.51
Total excessive speed under low-friction	2,919	7.53

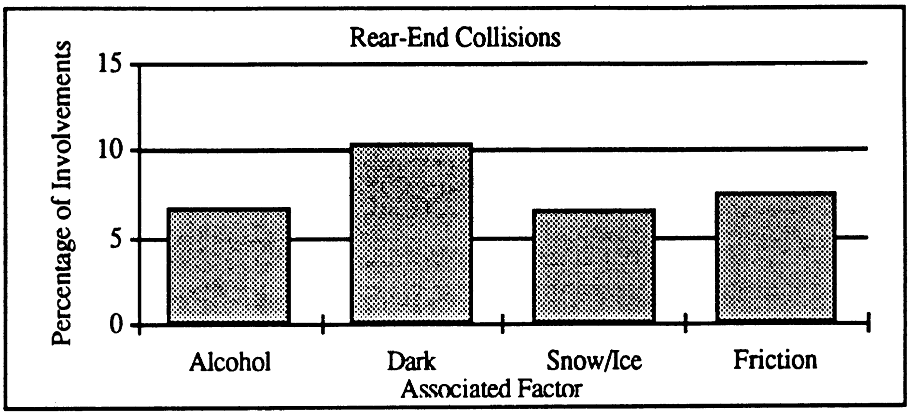


Figure 7. Associated factors of rear-end collisions.

Table 17. Head-on collisions.

N = 7,048 — 5.7 percent of all two-vehicle accidents; 3.9 percent of all single-vehicle accidents

	Frequency	Percent
Alcohol/drugs only	567	8.04
Dark, unlit only	584	8.29
Snowy/icy roads only (no speed)	920	13.05
Snowy/icy roads and speed-related	209	2.97
Wet and speed-related	324	4.60
Alcohol and dark only	377	5.35
Alcohol and snow/ice only (no speed)	42	0.60
Alcohol and snow/ice and speed-related	9	0.13
Alcohol and wet and speed-related	20	0.28
Dark and snow/ice only (no speed)	218	3.09
Dark and snow/ice and speed-related	58	0.82
Dark and wet and speed-related	38	0.54
Alcohol and dark and snow/ice (no speed)	35	0.50
Alcohol, dark, snow/ice, and speed-related	7	0.10
Alcohol, dark, wet and speed-related	12	0.17
None of the above	3,628	51.48
	7,048	100.00
Total alcohol/drugs	1,069	15.17
Total dark, unlit	1,329	18.86
Total snow/ice	1,498	21.26
Total excessive speed under low-friction	677	9.61

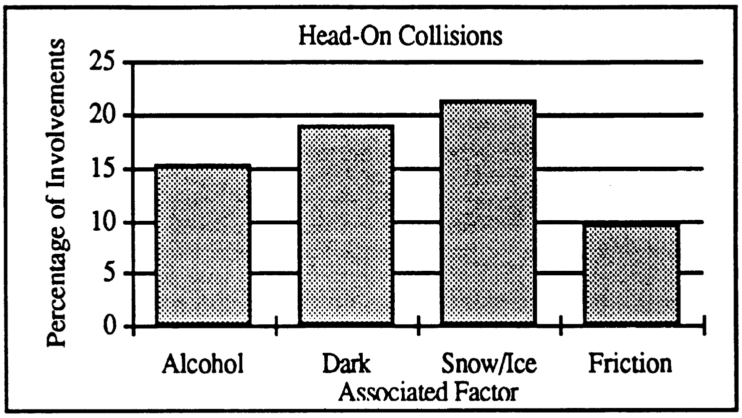


Figure 8. Associated factors of head-on collisions.

CHAPTER 4. DESCRIPTIONS OF POSTULATED COUNTERMEASURE SYSTEMS

THEORY OF DRIVING

The title, "Theory of Driving," may invoke a much more elaborate and more comprehensive set of concepts than the following material encompasses. Nevertheless, there are basic needs for having a model of the driving process that can be used in the context of this report. First, a simple model of the driving process is needed to provide a foundation for the descriptions of the postulated countermeasure systems that follow in this chapter. The model will be useful later in evaluating the philosophical logic of the postulated countermeasure systems as well as in predicting benefits. At this point, a theory of driving, albeit a very elementary one, provides a generalized rationale for countermeasure systems that are intended to aid the driver in selecting a traveling speed and performing the observation and control functions associated with crash prevention and avoidance activities.

In this theory, the driver and any equipment that aids the driver is envisioned as operating in one of three modes. The first mode has to do with setting or selecting a traveling speed consistent with the driver's purposes and the circumstances expected during the trip. Somehow, the driver arrives at a traveling speed through a decision process that may be a compromise among factors such as the desire to get somewhere in a timely manner, the perceived risk of a crash, the desire to see and interpret or appreciate sights along the way, speed limits and advisory speed information, and the level of concentration and effort the driver wishes to expend upon the driving task.

Once a traveling speed is established, the driver and associated equipment operate in a crash prevention mode (the second mode) in which diligence and vigilance in looking for hazards is a primary task. In this mode, speed may be adjusted to help compensate for risk perceptions. However, the main driving activity in this mode is centered on crash prevention activities such as maintaining adequate headway, staying in one's lane, etc.

The third mode is the crash avoidance mode in which braking and/or steering and perhaps accelerating activities are used to resolve conflicts that would lead to a crash if nothing were done about the conflicts. This mode follows from the crash prevention mode when the driver perceives a threat that calls for substantial control action. The success or failure of the control actions taken in the third mode depend upon the speed of travel, the distance at which the driver recognized the hazard, the alertness of the driver (the driver's reaction time), and the maneuvering (acceleration) capability of the vehicle which is limited by the existing level of tire/road friction. To an important extent, the success or failure of the crash avoidance control activity depends upon the activities and decisions inherent in the other two modes before the threat occurred.

With regard to driver factors associated with crashes, the Indiana study is often quoted.[5] Interpretations of the results of those in-depth investigations indicate that driver factors occur in nearly all crashes. See table 18 (from reference 6) for an interpretation of the information presented in reference 5. From the perspective of this theory of driving, the high percentages for driver factors are not surprising because the driver is the one controlling the vehicle and the one responsible for knowing if unfavorable or threatening conditions exist. Clearly, the driver determines where the vehicle will go. Barring some gross failure of the vehicle or some extraordinary environmental or roadway disaster, the driver is responsible for maintaining adequate control for avoiding crashes and for not trying something risky. The countermeasure systems envisioned here have the goal of aiding the driver in all aspects of vehicle control and crash avoidance. The idea is that there are clearly circumstances that are beyond the crash prevention and avoidance capabilities of drivers (otherwise there would be almost no crashes).

In summarizing the basic elements of our approach, driving is envisioned as consisting of three basic tasks: regulation of speed, control of direction and headway, and resolution of conflict. How well these tasks are performed depends upon the alertness of the driver, the decision information that is comprehended by the driver, and the maneuverability of the vehicle.

To help in understanding how advanced technology may improve the driving process, the subjects of vehicle control, driver reaction time, vehicle maneuvering capability, preview distance, and the use of a codriver system have been examined in this study. Pertinent results, findings, and perspectives are included here under the theory of driving.

Table 18. Factors that cause accidents.[5,6]

Cause	% Accidents	
Driver	96.2	
improper lookout	23.1	
inattention	15.0	47 % failure to observe
internal distraction	9.0	
improper evasive action	13.3	
false assumption	8.3	33.8 % poor maneuvering
improper maneuver	6.2	
overcompensation	6.0	
improper driving technique	9.0	17.8 % headway
inadequate defensive driving	8.8	
excessive speed	16.9	16.9 % velocity
other (blackout, dozing, etc.)	5.8	5.8% impairment
Environmental	33.8	
view obstructions	12.1	
slick roads	9.8	
transient hazards	5.2	
design problems	4.8	
control hindrances	3.8	
inadequate signs & signals	2.9	
other (road maintenance, etc.)	1.6	
Vehicular	12.6	
gross brake failure	3.1	
inadequate tire depth	2.6	
brake imbalances	1.9	
tire underinflation	1.4	
vehicle-related vision obstructions	1.0	
other (steer, powertrain, etc.)	3.2	

With regard to vehicle control, the following basic premises have been stated:[7]

- Active safety is the study of vehicle control, where better control implies fewer crashes.
- Vehicle control involves previewing the driving situation to assess the need for crash avoidance actions. Furthermore, there is a relationship that indicates that the shorter the available preview of the crash threat, the greater the intensity of the action required to avoid the crash.
- Control capability depends upon having sufficient preview to provide adequate reaction time and maneuvering space. There is an analogy here to the way that highway engineers have used stopping-sight distance to design crest vertical curves.[8] Conceptually, stopping-sight-distance is the distance required to provide line-of-sight visibility. The line-of-sight should be long enough to allow drivers time to recognize that there is an object in the road and then to be able to stop the vehicle before reaching that object.

(In general, it might be said that roads are designed with the goal of allowing drivers to see far enough to be able to avoid hazardous situations if they happen to be present. Perhaps, in addition to other features, new technology will provide means for "seeing" around corners, through the dark or fog or dust, or over hills.)

The introduction of active-safety technology provides new methods for achieving improved vehicle control. Figure 9 shows salient features of the vehicle control situation. If the block labeled "ACTIVE SAFETY TECHNOLOGY" were to be removed, the figure would illustrate the driver-vehicle-roadway system as it functions now. The driver senses, recognizes, decides, and actuates the controls in response to an overall input called "preview" in the figure. The length of time from when a threat could have been detected (usually seen) until when the driver takes action is designated as the "reaction time." When active-safety technology is added to the system, there are now more inputs to the driver and there is the possibility for control interventions that are faster than the control actions provided by the driver. For an ideal active-safety system, the correct response to threats would be made sooner, quicker, and more reliably than when the driver was operating alone. The active-safety system should compensate for driver shortcomings by providing not only quicker responses, but also better perception, improved vigilance and diligence, and better choices of control actions and traveling speeds.

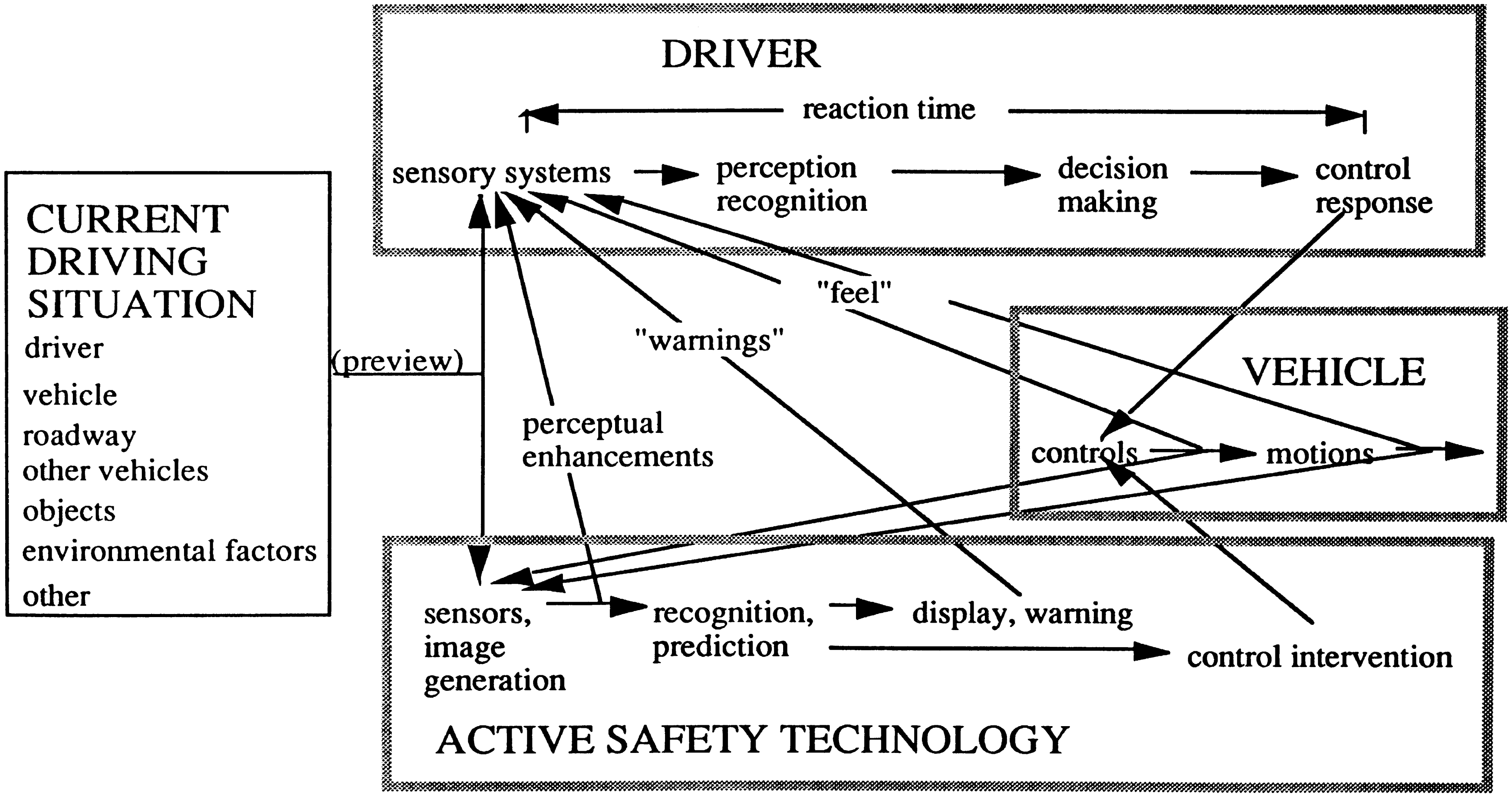


Figure 9. Salient features of the vehicle control situation.

In the IVHS arena, results pertaining to the benefits of an additional 0.5 s are often quoted.[5] By studying data on the velocity of vehicles at impact, it has been projected that an additional 0.5 s of warning could eliminate 50 percent of all rear-end and intersection-related crashes and 30 percent of crashes with oncoming traffic.[9] The ideas behind these projections are illustrated for a braking situation in figure 10. In this example the velocity at impact is 8 ft/s. If the vehicle could have continued to decelerate at 16 ft/s^2 for another 0.5 s, the crash would have been avoided. This means that if the stopping sequence had started 0.5 s earlier (see figure 11), the vehicle would have stopped short of the crash. The crash data show that many crashes are like this example in that the vehicle slowed down, but not soon enough before the crash.

The situation shown in figure 10 is useful for illustrating the effects of other actions besides providing another 0.5 s of warning. For example, if the initial traveling speed had been 8 ft/s slower (see figure 12), the crash would have been prevented. If the driver's reaction time had been 0.5 s shorter (see figure 13), the crash would have been avoided. If the deceleration rate had been 0.55 g instead of 0.5 g (see figure 14), the crash could have been prevented. All of these examples illustrate opportunities where advanced technology can help.

The sketches in figures 10 through 14 contain allowance for reaction time and maneuvering time. These are key elements of the theory being developed.

When the time to impact is short, the maneuver needs to be drastic enough to avoid the crash. Examination of figure 10 shows that 0.5 g would not be enough deceleration for the time available. As indicated in figure 14, 0.55 g was needed.

The examples used so far pertain to braking, but similar results can be obtained for swerving maneuvers to avoid obstacles or for maneuvers to change heading for negotiating sudden curves or to correct for running off the road. These matters will be covered later in developing relationships to be used in the design of countermeasures.

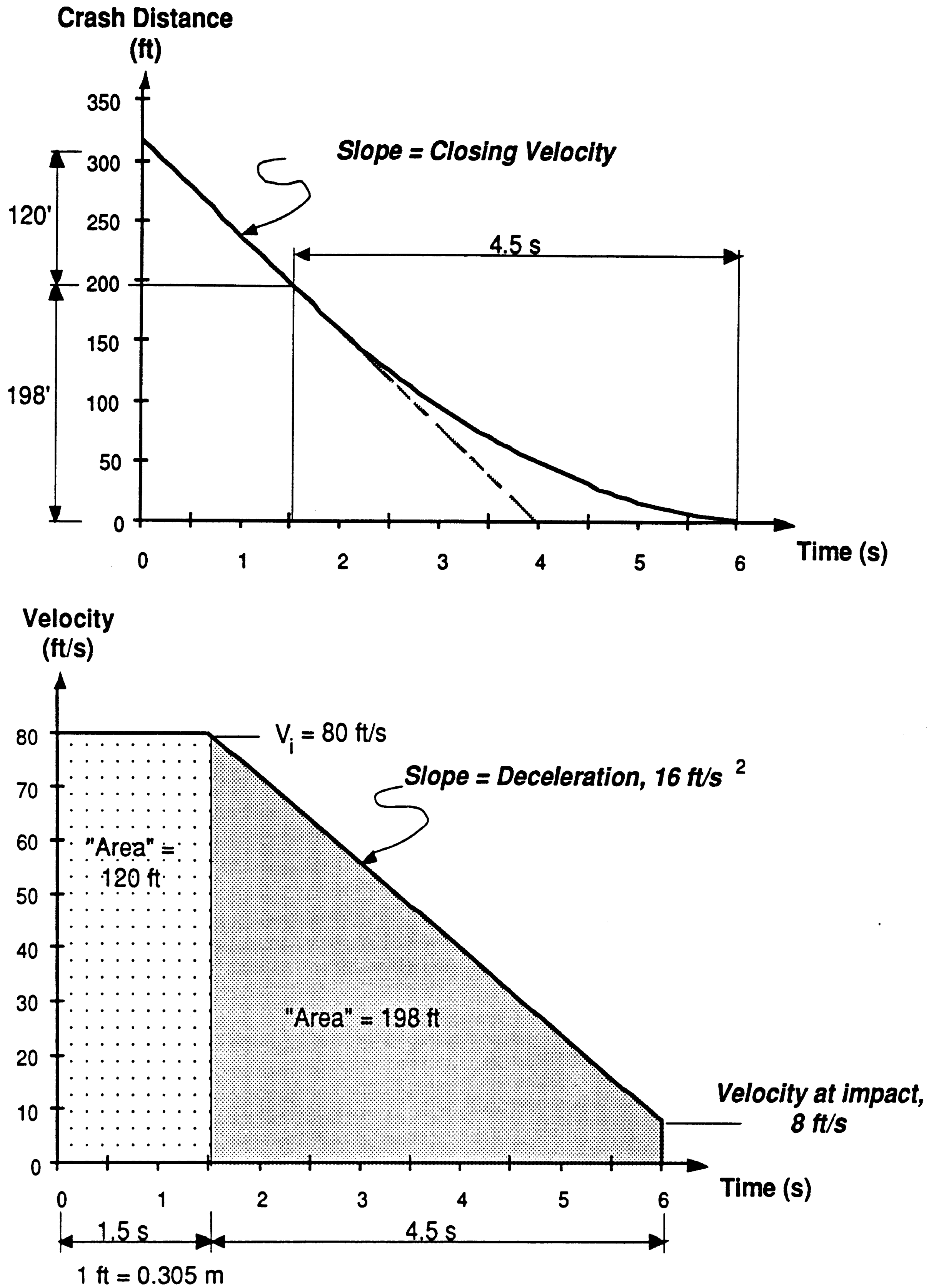


Figure 10. Rear-end crash at 8 ft/s, 0.5 g deceleration, 1.5 s delay.

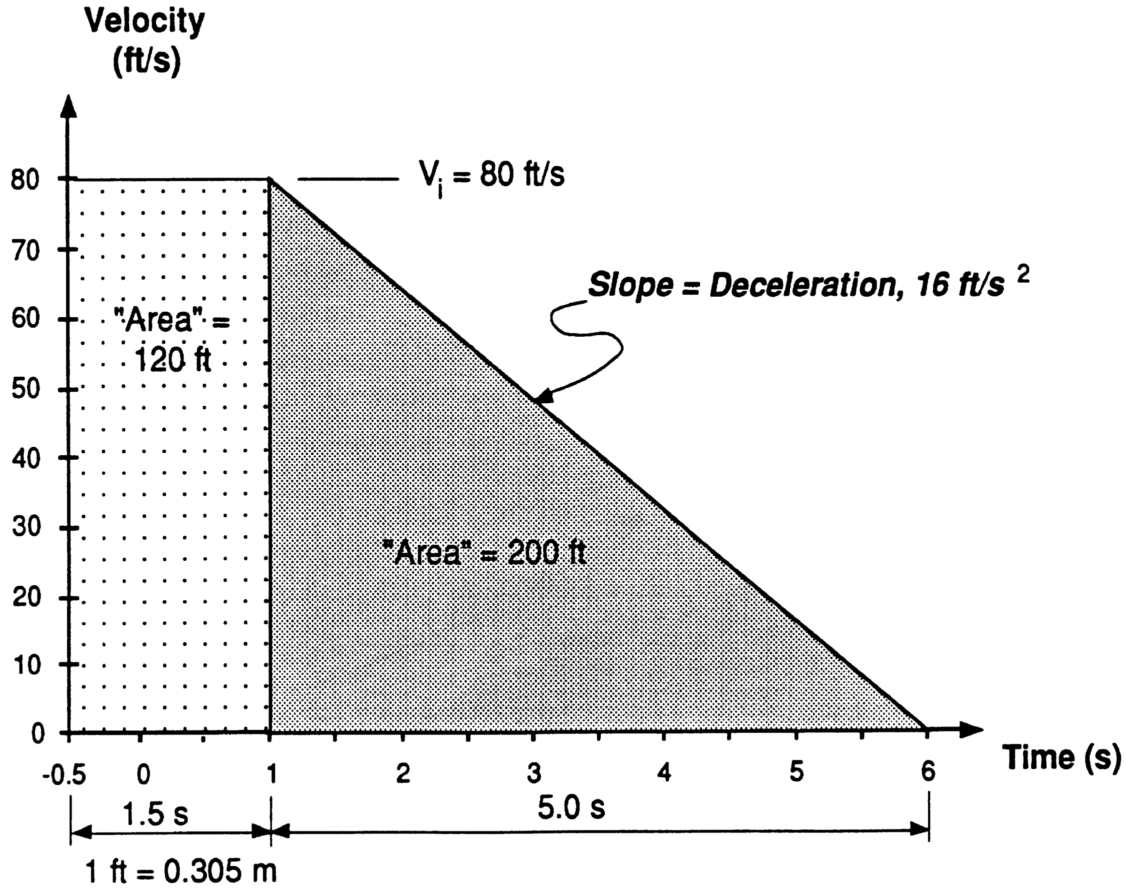


Figure 11. Crash avoidance by starting 0.5 s sooner.

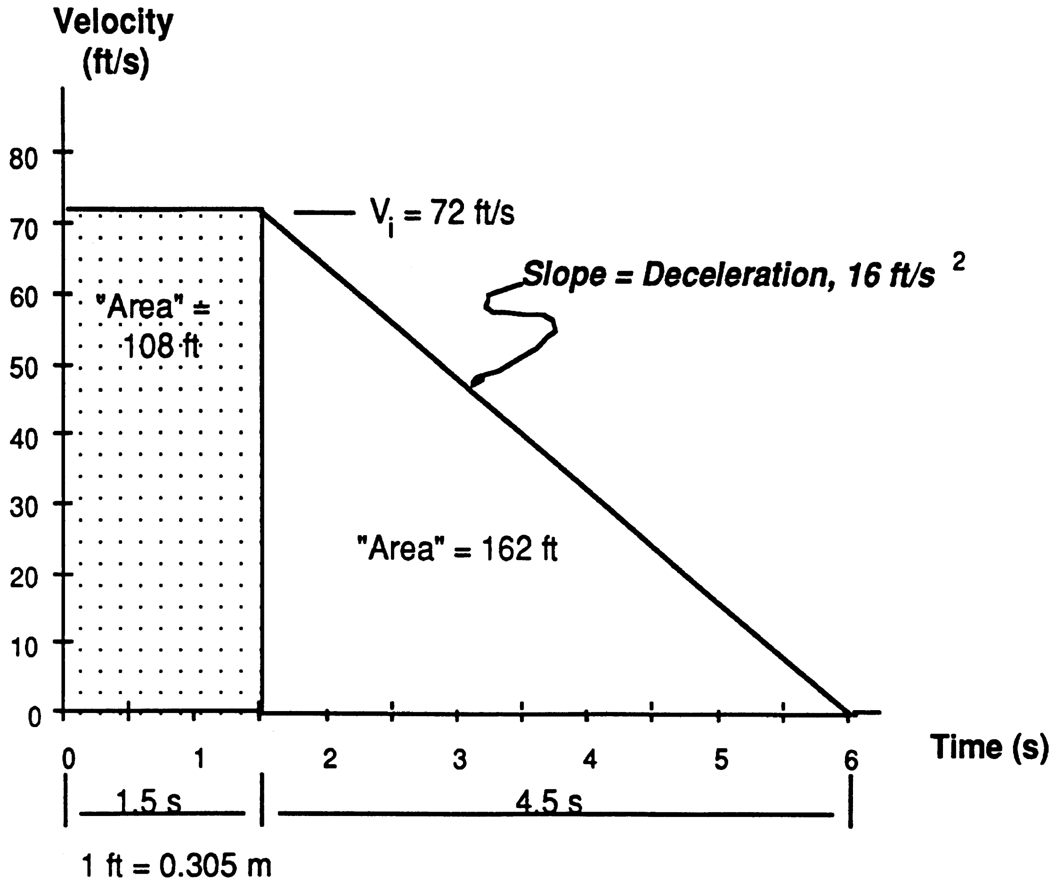


Figure 12. Crash avoidance by lowering the initial velocity to 72 ft/s.

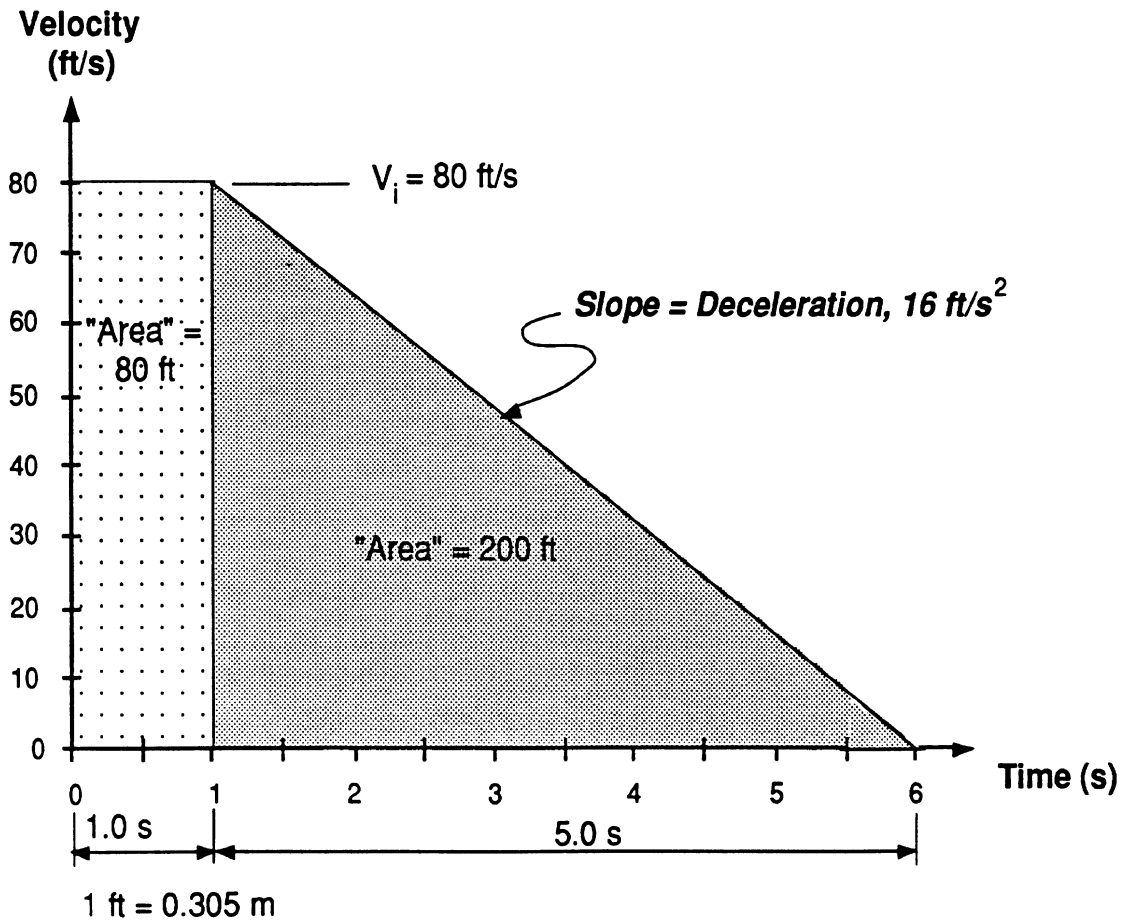


Figure 13. Crash avoidance by shortening driver reaction time to 1.0 s.

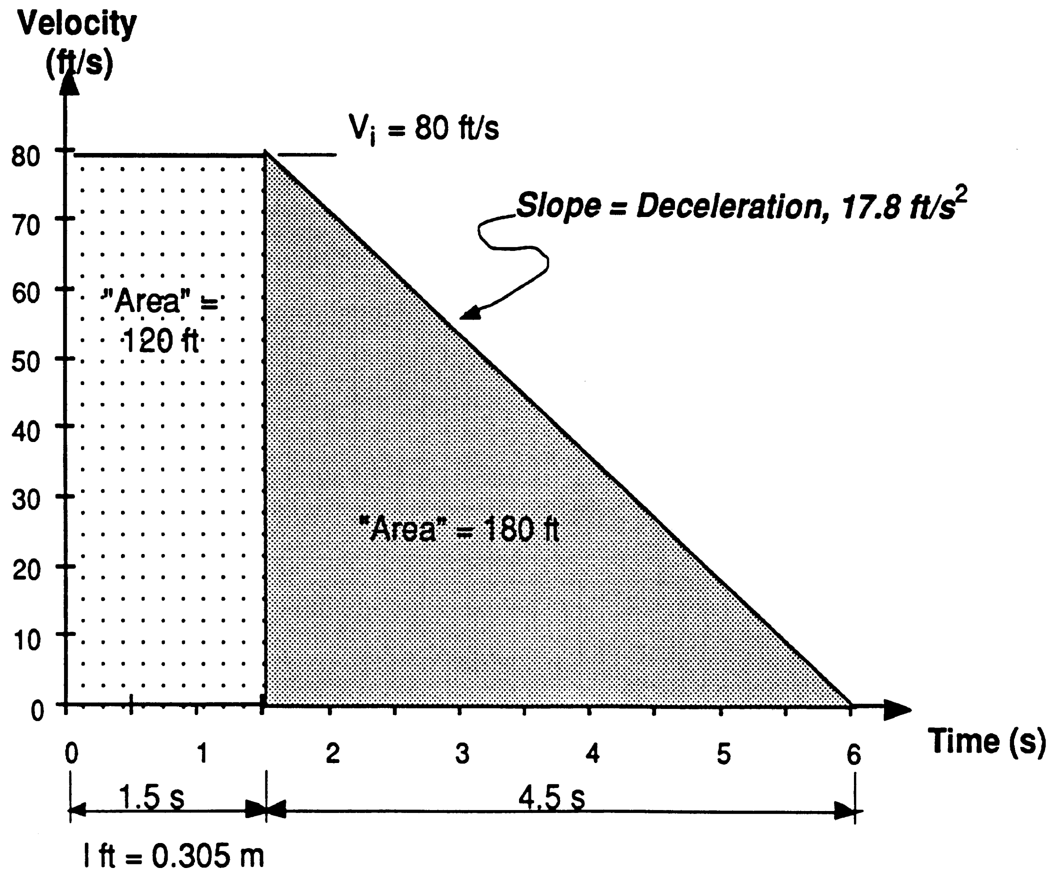


Figure 14. Crash avoidance by increasing the deceleration level to 17.8 ft/s^2.

In addition, it has been implicitly assumed that there was enough tire/road friction to accomplish the control action demanded. In recent years, technology has been employed to develop vehicles that can use a large percentage of the tire/road friction available to them. The use of anti-lock braking systems (ABS), four-wheel steering (4WS) , and active suspensions (AS) have contributed to greater capability to use the maximum available tire forces for controlling the vehicle without the vehicle going out of control.[10] To the extent that drivers notice this extra capability, they may feel safer. This may cause them to take compensatory risks (risk compensation). For example, they might tend to operate their vehicle closer to the friction limit than a prudent crash prevention strategy would dictate.

An important, albeit obvious, observation is that friction places an upper bound on the intensity of the control action possible. It is convenient to think of the friction coefficient as a first order limit on the acceleration that a vehicle can perform. (That is, the friction coefficient as a numerical quantity is greater than the maximum acceleration the vehicle can attain where this acceleration is expressed in g's.) A modern vehicle with high braking efficiency and lateral efficiency will be controllable and able to use much of the friction available in crash avoidance maneuvers but it cannot perform above the level allowed by the tire/road friction.

The notions of reaction time and maneuvering distance are not new vehicle-control concepts for use in designing countermeasures for crashes. They have been used in highway design policy for many years.[8] They are crucial in designing highways. Roads are built with sight distances that allow drivers to see far enough to avoid pertinent types of crashes. The concept of stopping-sight distance is a prime example. A crest vertical curve is designed with a curvature that will provide enough sight distance for a slowly reacting driver to stop before hitting an obstacle on a poor, wet road. Highway design policy is based upon relationships involving the use of vehicle speed, driver reaction time, vehicle deceleration capability, and braking distance to determine sight distance.

Now considering the design of countermeasure systems, the following basic premises have been postulated:[7]

- The design synthesis of a countermeasure system requires ingenious thinking associated with envisioning a concept to be implemented through technology. The idea here is that the era of active-safety technology is at a beginning stage in which invention plays an important role. Nevertheless, the discussion of functional needs may lead to the insight and ingenuity required to envision useful applications of active-safety technology.
- There are relationships involving reaction time and maneuvering distances that can be used as design relationships to formulate functional goals for

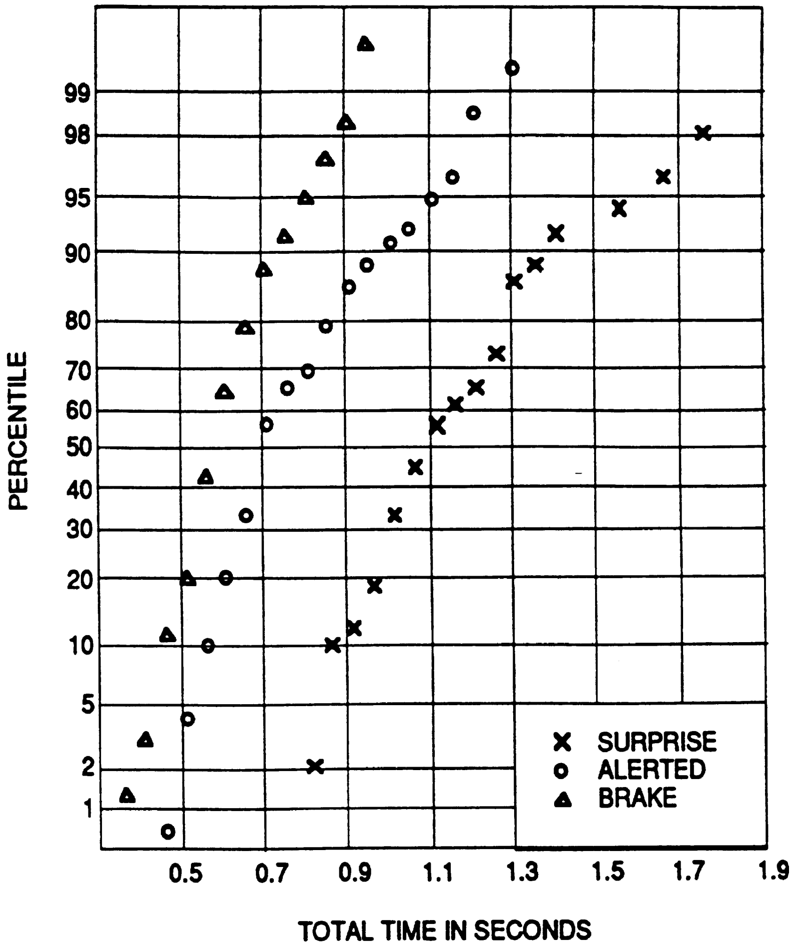
active safety systems. These relationships generally indicate available tradeoffs between reaction time, distance, traveling speed, and the intensity of the action chosen. The relationships currently used in reference 8 for expressing the influences of driver reaction time and braking distance on stopping-sight distance for roads with various design speeds are analogous to the types of relationships envisioned here.

- A basic functional goal of all active-safety systems involves a statement concerning the range of the sensing system. The range of the sensing system in a crash-type-specific system corresponds to the maximum preview between the vehicle to be protected and the hazard to be avoided. In somewhat analytical terms, a goal for crash-type-specific systems is to have the range of the sensor greater than the reaction time multiplied by the speed of travel plus the maneuvering distance, which is a function of the speed of travel. In cases where practical systems have limited range, there may be a need for adjusting traveling speed to allow active-safety systems enough preview to be effective in aiding in avoiding crashes.
- The above statements concerning sensor range apply to crosscutting countermeasures but in a different or indirect manner. Functional goals for crosscutting countermeasures involve the distance and time consumed in bringing the operation of a driver-vehicle-roadway (DVR) system (i.e., one of the DVR systems in the overall DVR system) to an acceptable level of performance capability. Sensing systems that observe operational qualities like driver alertness, visibility, tire/road friction, etc. are not directly associated with the range or time to a specific type of crash threat. Rather, these operational qualities impact on the ability to respond to a crash threat if one were present. The lack of adequate capabilities for responding to crash threats may contribute to a particular type of crash, in particular, head-on collisions. Important issues here are how long and at what speed will the vehicle be operating with inadequate control capabilities in terms of reaction times and maneuvering distances. Important questions to answer are: How quickly will the operational problem be sensed and corrected or compensated for? What level of crash avoidance capability should be used as a guide in setting functional requirements for crosscutting countermeasures addressing operational problems?
- There are design goals concerning false alarms and missed threats. Perhaps, there may be cases in which the false-alarm rate becomes prohibitively high beyond a certain range. For example, it might be that the possibility of a rear-end crash is very small if the range to the vehicle ahead is over 300 ft, but the possibility of a warning being issued is fairly large for a particular countermeasure system. In this case, the false-alarm rate could: (1) set a limit on the useful range of the system and (2) have a bearing on when warnings are issued. There could be additional general statements regarding these matters, but perhaps design targets that are specific to each proposed countermeasure system or type of system need to be developed on a case-by-case basis. The idea of an evaluative test comes to mind in judging these qualities (as it does

for other aspects of these systems). In general, a test involves performance goals (outputs) that are associated with known, measured, or specified inputs. In an evaluative test, there are usually performance metrics (measures) that can be used to indicate how close the system comes to meeting its performance goals. Ideally, the design process would include statements of performance goals and an indication of how the performance of prototype systems or proposed designs are to be evaluated.

The concepts presented in this part of the theory of driving are based upon thinking about: (1) crosscutting countermeasures pertaining to driver alertness, visibility, and tire/road friction and (2) crash-type-specific countermeasures for the crash types like those selected from the study of the CARDfile. Basic design relationships can be derived explicitly from considerations of crash scenarios like rear-ends or impacts with objects in the road. The use of these design relationships in crosscutting and intersection situations is not necessarily straightforward, but nevertheless useful. Reaction time and maneuvering distance play a prominent role in the relationships discussed here.

Reaction time—The situation with regard to reaction time is portrayed by the example given in figure 15.[11] The figure shows three curves depending upon whether: (1) the driver was responding to a light mounted on the hood of the car, (2) the driver had been forewarned that there would be a hazard in the road, or (3) the driver was taken by surprise. The data indicate the percentages of drivers using less than a specified reaction time. Typically 85th percentile or higher levels of reaction time are used in highway design. For active-safety systems, a goal might be for a display or warning system that was so good that the 85th percentile reaction time was as short as the 85th percentile value for the light mounted upon the hood. This may be an upper boundary on expectations. Perhaps something like the 85th percentile for the alerted driver would be a more reasonable goal. In any event, a functional goal pertaining to reaction time is reasonable, and that goal might provide an important portion of the additional time provided for braking or maneuvering.



Driver perception-response time—"Surprise" and "alerted" trials were measured from first sighting of an obstacle in the road until the driver's foot contacted the brake. Subjects (n=64) were not aware of the purpose of the test on surprise trial, but were on alerted trials. "Brake" trials were measured in a moving car from onset of a hood-mounted light until brake pedal was contacted.

From Olson, Cleveland, Fancher, Kostyniuk, and Schneider (1984).[11]

Figure 15. Reaction time.

Maneuvering distance—With regard to maneuvering distance, example design equations can be developed from simple kinematic considerations. These equations are useful for analyzing situations like those portrayed by figures 10 through 14. The following simple equations provide first-order estimates of vehicle performance as expressed in terms of traveling speed, the maximum acceleration level involved, the time period of the maneuver, and the time to impact from when the maneuver was started.

For braking distance D_b:

$$D_b = V_t^2 / 2 \cdot A \tag{1}$$

where V_t = traveling speed and A = average deceleration level.

For swerving distances, Dsy (lateral displacement) and Dsx (longitudinal distance):

$$Dsy = A \cdot T^2 / 6.28 \tag{2}$$

where T = the period of the maneuver and A = peak lateral acceleration.

$$Dsx = V_t \cdot T. \tag{3}$$

For heading changes, $\Delta \phi$ (angular change) and $D\phi$ (longitudinal distance):

$$\Delta\phi = r_m \cdot T / 2 \tag{4}$$

where r_m is the maximum yaw rate and T is the period of the maneuver.

$$D\phi = V_t \cdot T \tag{5}$$

Equations 2 and 3 are based upon a lateral-acceleration time history corresponding to one cycle of a sine wave. Equations 4 and 5 are based upon a yaw-rate time history of the following form:

$$r = (r_m/2) \cdot (1 - \cos 6.28\, t / T) \qquad \text{for } 0 \le t \le T \tag{6}$$

where r = yaw rate, r_m = the maximum value of the yaw rate, t = time, and T = the period of the cycle. For t > T, r = 0.

The above equations are very simple. They are intended to be that way in order to be useful for a first cut look at design situations. Clearly, more sophisticated analyses and simulations could be employed once detailed descriptions of countermeasure systems are available. The above equations are intended to be sufficiently representative of the kinematics of vehicle motions to be meaningful in relating acceleration levels to the velocities, times, and distances corresponding to typical crash-avoidance maneuvers.

With regard to swerving maneuvers, two-lane highways have passing and no passing zones. If the driver of another vehicle makes a poor judgment as to when and where to pass, a very quick maneuver may be needed to avoid a crash with that vehicle. There may be enough sight distance to stop for a fixed-object in the road even in no passing zones, but the sight distance may not provide adequate warning if there is a vehicle coming rapidly or suddenly in your lane. In these situations, swerving might be the answer because it is quicker than stopping and braking may not resolve the conflict. Difficulties with swerving involve which way to go and whether there are other hazards to consider. Nevertheless, as a measure of last resort, the driver may need to use a swerving maneuver. Even so, appropriate countermeasures for preventing head-on crashes may involve attempting to keep vehicles in their lane when it is not reasonable or appropriate for them to enter another lane.

Safetec—An advanced technology safety management system—Safetec, as presented here, represents a conceptual overview of a means for combining the functional components of several countermeasure systems into a safety management system that could play the role of a codriver. The functional characteristics of Safetec involve sensing the driving environment, recognizing hazards, selecting countermeasures, and implementing preventive or avoidance actions. This structure is based upon a concept of "instant-to-instant safety" that asserts that highway safety is currently determined by the actions (including lack of action) taken by the drivers traveling at any given moment in time. In a sense, Safetec is a system that augments basic (classical) driver, vehicle, and roadway capabilities for responding to the demands present in the driving environment at a specific place and time.

Safetec focuses on the driver, the vehicle, and the road system as an integrated whole whose various elements are made to interact. It has been created to be part of an evolving safety program consisting of: (1) knowledge—understanding the demands and the capabilities of the driver-vehicle-roadway (DVR) system that are associated with particular accident situations and, in addition, the prevalence, risk, and severity of various accident types, (2) prevention—eliminating hazardous situations, and (3) avoidance—avoiding crashes in hazardous situations (when hazards occur despite efforts to eliminate them). In creating Safetec, the goal has been to work from the ideas generated in our brainstorming sessions and our knowledge of existing accident data bases to envision a safety management system that would act first to prevent hazardous situations and then, if hazards still occur, to take emergency actions to avoid crashes.

To define the Safetec system more specifically, the following types of subfunctions are indicated for each of the safety-related functions (actions and purposes) to which Safetec applies:

- Sensing or observing pertinent features of the driving situation.
- Recognizing "abnormal" sensations or observations.
- Deciding if preventive or avoidance actions are in order.
- Implementing actions that are appropriate to the current driving situation.

Figure 3 is a block diagram that illustrates and summarizes the overall structure of the Safetec system. As indicated in the figure, Safetec employs a predictive model to complete the process of selecting the countermeasure(s) to be implemented. Currently, this model is envisioned as covering a broad range of situations ranging from something like "if the driver is told to slow down because the road is slippery ahead, the driver will be forewarned in time to prevent sliding off the road into the guard rail" to something like "the closing rate to the vehicle ahead is too great for the distance and speed involved, apply the brakes hard enough to get the driver's attention now so that a rear-end accident will be avoided." Even though the details of the predictive model are still vague, the idea of being alert to multiple driving hazards is certainly a part of the theory of driving and there appears to be a need to coordinate any set of countermeasures to prevent them from interfering with each other.

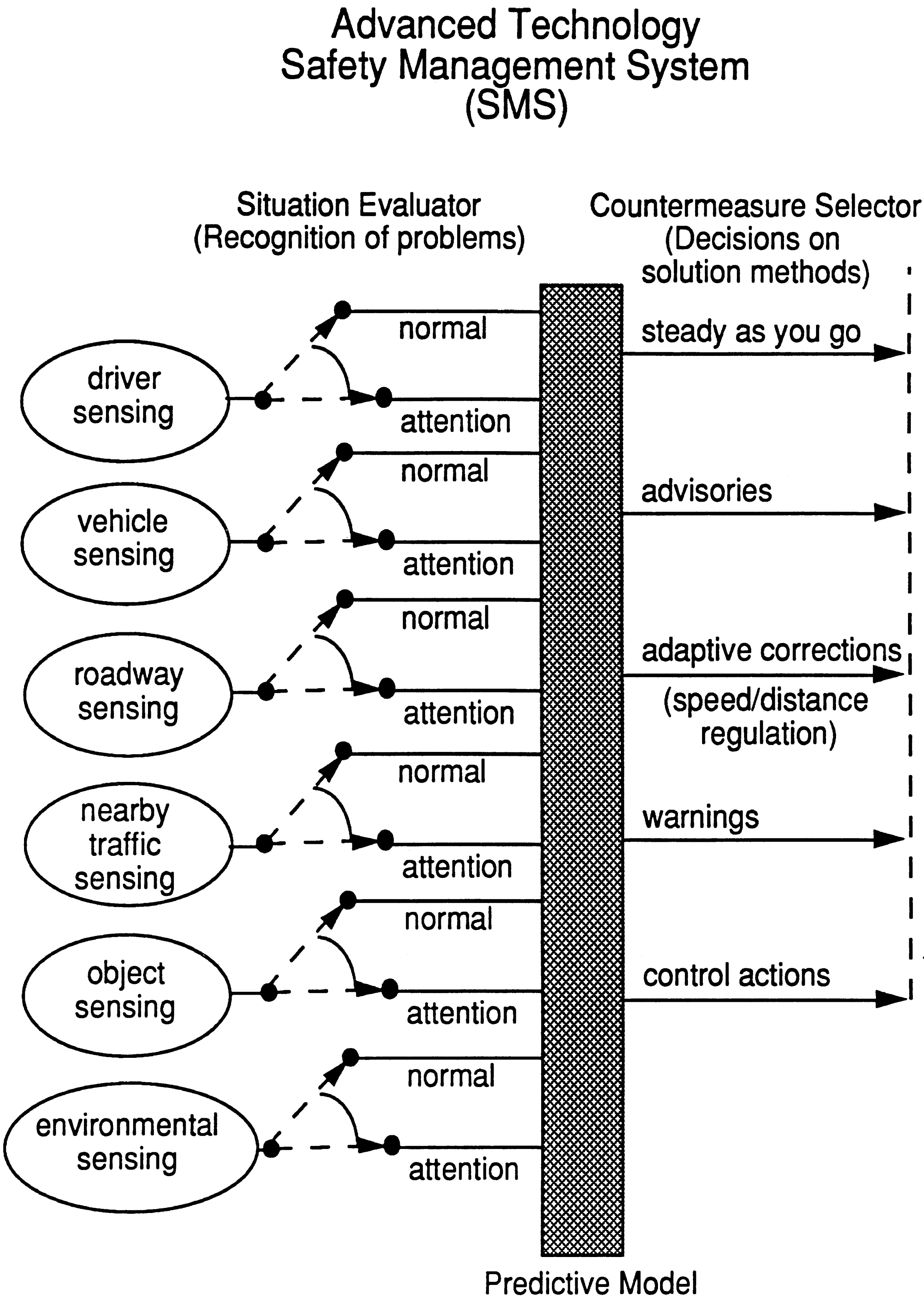


Figure 16. Overall structure of the Safetec system.

COUNTERMEASURE SYSTEMS

The following material contains descriptions of eighteen countermeasure systems aimed at six predominant accident types identified earlier through an examination of crash data files. Based upon sorting the crash data into a typology of crash types, the following scenarios were selected for study:

Single-vehicle crash types:

1. Run-off-road.
2. On-road collision with pedestrians, objects, animals, etc.

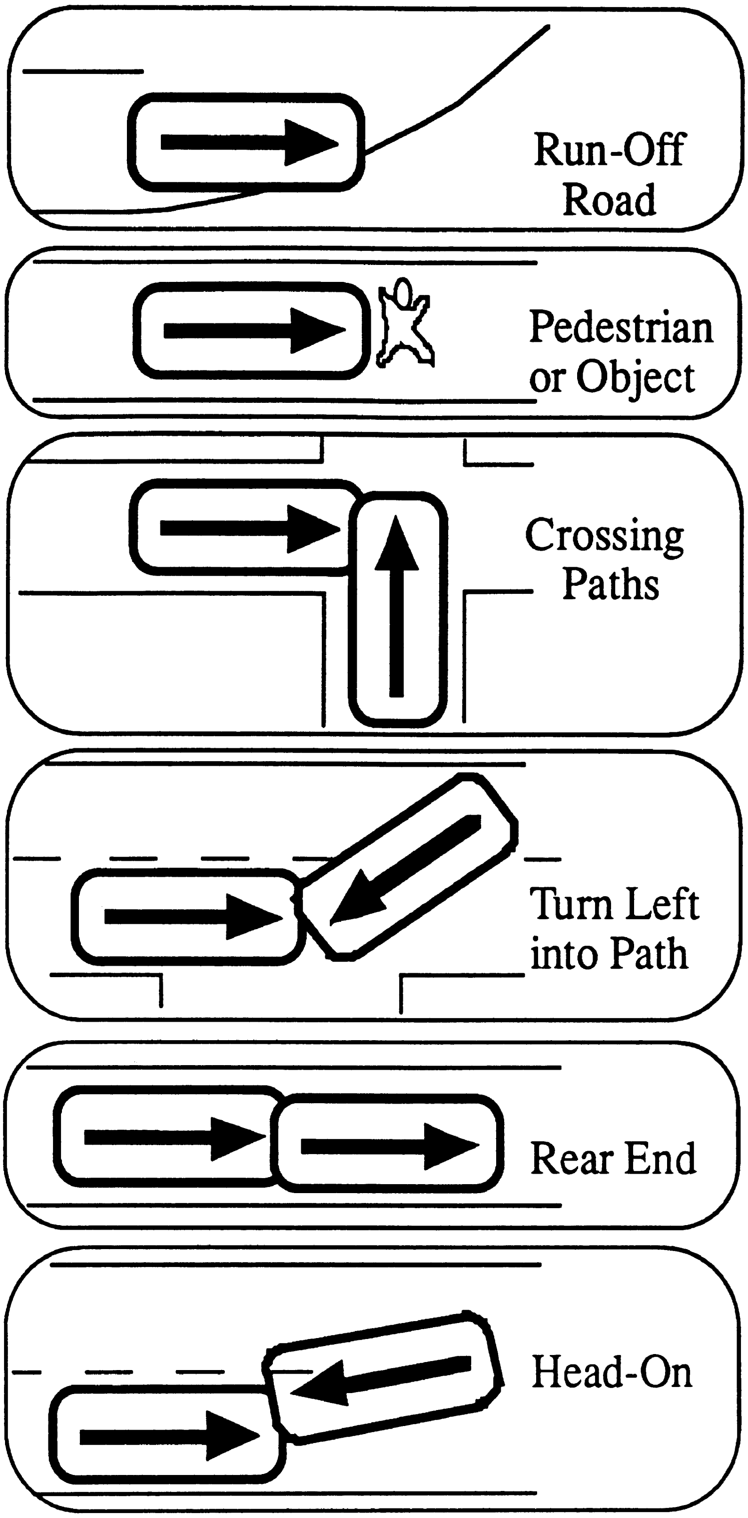
Two-vehicle crash types:

3. Rear-end.
4. Crossing-path collisions at intersections.
5. Left turn crashes at intersections.
6. Head-on.

These crash types and their frequencies of occurrence are illustrated in Figure 17. The accident percentages given in figure 17 provide the means for making first order estimates of the gains attainable in reducing crash occurrences.

Two types of countermeasure systems, "crosscutting" and "crash type specific," have been developed for addressing the factors associated with the six crash types. Four of the countermeasure systems apply generally to all six crash types. The other 14 countermeasure systems are aimed at factors involved in individual accident types.

The countermeasure functions are named, numbered, and listed according to countermeasure type and crash scenario in table 19. Examination of the names in table 19 indicate that there are many warning systems involved. In some cases, control interventions are proposed. In one case (dark/unlit driving), a night vision system for perceptual enhancement is considered.



Crash type	Accident % S-V	Accident % 2-V	Accident % Both
Run-Off Road	57.5	--	17.7
Pedestrian or Object	20.1	--	6.2
Crossing Paths	--	18.1	12.5
Turn Left into Path	--	9.1	6.3
Rear End	--	31.2	21.6
Head-On	--	5.7	3.9
Totals	77.6	64.1	68.2

Figure 17. Six predominant crash types.

Table 19. Countermeasure systems listed by system type and crash type.

Cross cutting systems :(pertaining to all accident types)

1. Night vision perceptual enhancement for dark/unlit situations (might also be useful in fog or dust).
2. Driver impairment warning for erratic behavior.
3. Vehicle-based friction/ice detection and warning system.
4. Roadside friction/ice detection and warning system.

Crash type specific systems:

Single vehicle run-off-road

5. Lateral lane edge detection warning and steering correction.
6. Lateral lane edge detection warning and steering correction with lateral and longitudinal preview.
7. Dynamic horizontal curve speed advisory and control.

Pedestrians, objects, etc. in the road

8. Longitudinal control for objects in the roadway.
9. Presence of pedestrians at midblock crosswalks.

Rear-end crashes

10. Headway control based upon adaptive cruise control.
11. Short headway time and/or distance warning.

Head-on

12. Warning of the presence of on-coming vehicles (cooperative vehicles).
13. Warning of the presence of on-coming vehicles (road-based system).
14. Lane-keeping using a detectable line in the center of the lane (virtual monorail).

Intersection crossing paths

15. Warning of the presence of vehicles on a major road (stop and yield).
16. Warning of the presence of vehicles on a minor road (stop and yield).
17. Cooperative intersection: four-way stop right-of-way indicators.

Intersection left turn

18. Approaching vehicle warning for driver making a left turn / also warning of a vehicle turning left.

In summary, based upon preparing descriptions of these countermeasure systems, there are two complementary thrusts involved here: (1) enhanced situation awareness to aid the driver in identifying possible conflicts and (2) variable messages that (a) change in real time to reflect the existing situation, (b) extend the awareness distance beyond the available sight distance on the road, and (c) provide information and control actions that aid drivers in adjusting speed and direction as needed to respond to the current driving situation.

The following chapter is composed of descriptions of each of the countermeasure systems. Although the systems for performing the various countermeasure functions may be quite different, the descriptions of them contain sections on the following items:

- General concept.
- Presentation to the driver.
- Sensing the driving situation.
- Performance and functional specifications (if not already defined).
- Equipment needs.

Regardless of the format, each description is aimed at presenting a clear picture of a distinct countermeasure concept. Diagrams and sketches are used as appropriate to illustrate: (1) the concept, (2) the locations of key pieces of hardware, and (3) the organization of a system for performing the countermeasure function.

Fundamental ideas regarding how technology can be applied to the equipment needs and functional requirements for the countermeasure systems are given in chapter 5 of this report. Further information on benefits and costs are given in chapters 6 and 7.

The following subsection contains write-ups on each of the individual countermeasure systems in the order indicated in table 19. One should realize that these systems are the result of creative processes that have involved a wide range of thoughts in outlining the features of each particular countermeasure system. Hence, the description of the detailed ideas used in outlining one countermeasure system may have either little correspondence to those used in creating another system or some of the ideas may be very similar.

Night vision enhancement

General concept

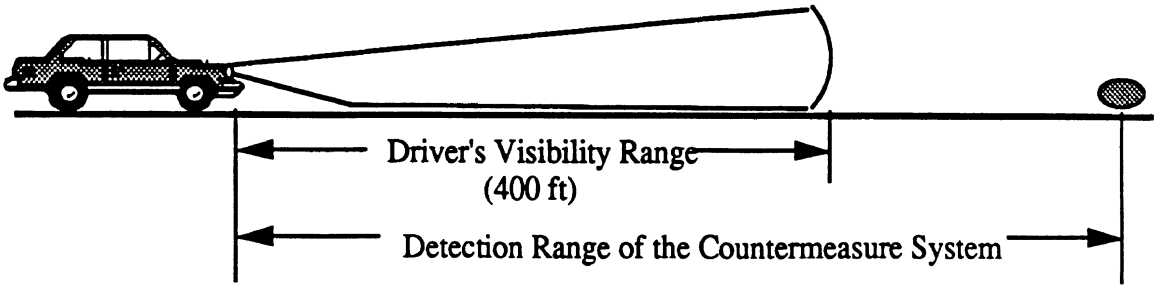
This countermeasure addresses poor nighttime vision which is a common problem among many drivers. Although, more of a concern with older drivers, certain conditions, such as rain, fog, and scotomatic glare can substantially reduce any driver's ability to clearly see and process events as they unfold. The system envisioned will enhance the driver's awareness of the road conditions ahead. A schematic diagram of the system is given in figure 18. The driver would be given a visual representation of the road that would have range great enough for the driver to have time to avoid a fixed object in the road. This system would provide an advisory speed that is consistent with the detection range of the system. Figure 19 shows the driver's view of the system. This countermeasure is relevant in run-off-road, vehicle strikes pedestrian/cyclist/animal, rear-end, and head-on collisions.

Presentation to the driver

The presentation is an enhancement of the driving scene in either a dash board-mounted monitor or using the relatively new technology called head-up display. An advisory speed and alarm would also be incorporated to alert the driver of an inadequate maneuvering distance for the current velocity.

Sensing of the driving situation

An infrared system (either active or passive) will produce an enhanced image of the driving scene and display it to the driver. (Technologies other than infrared might be considered as long as they are able to penetrate darkness satisfactorily.) If head-up technology is used, the scene will overlay the actual driving scene. The advisory speed would be calculated using both the infrared system and reaction time constraints and then displayed on the speedometer. The speed advisory alarm would be an audio warning when the driver's speed exceeded that advised. The driver will be able to independently turn each system on or off depending on its necessity.



1 ft = 0.305 m

Figure 18. Visibility enhancement diagram.

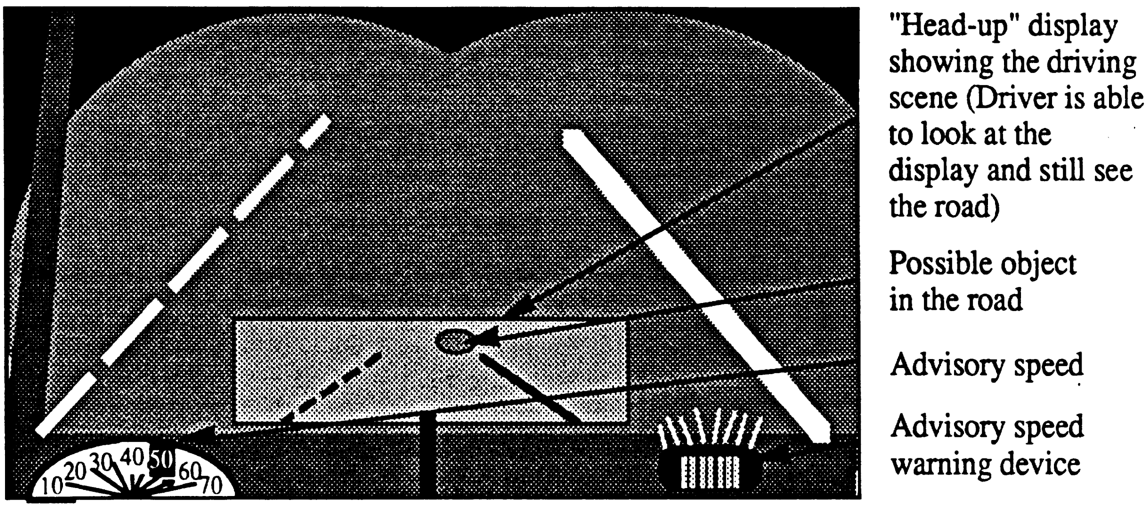


Figure 19. Head-up display and advisory speed warning devices.

Performance and functional specifications

Time and intensity levels involved — The goal of the system is to allow the driver to react one second sooner than the driver would react without the system. The range of the system has to be greater than the driver's reaction time times the target speed plus the maneuvering distance.

Vehicle motion ideas and constraints — For this particular scenario the system will have to provide enough time for the driver to slow the vehicle to a stop before reaching the pedestrian, animal, or object. The desired range of the system is:

$$(R_t + E_t + P_t) * V + V^2 /(2g(f+G))$$

Where:

R_t is reaction time of driver

E_t is amount of earlier reaction time desired

P_t is processing time

V is velocity of vehicle in ft/s

f is the coefficient of friction between tires and roadway

G is grade in radians

g is 32.2 ft/s^2

A value for f can be obtained from either direct measurement or an estimate from the velocity and some of the other variables that can be sensed, i.e., temperature, wetness of road, some surface characteristics, etc. It is assumed that we can measure the grade of the roadway from within the vehicle.

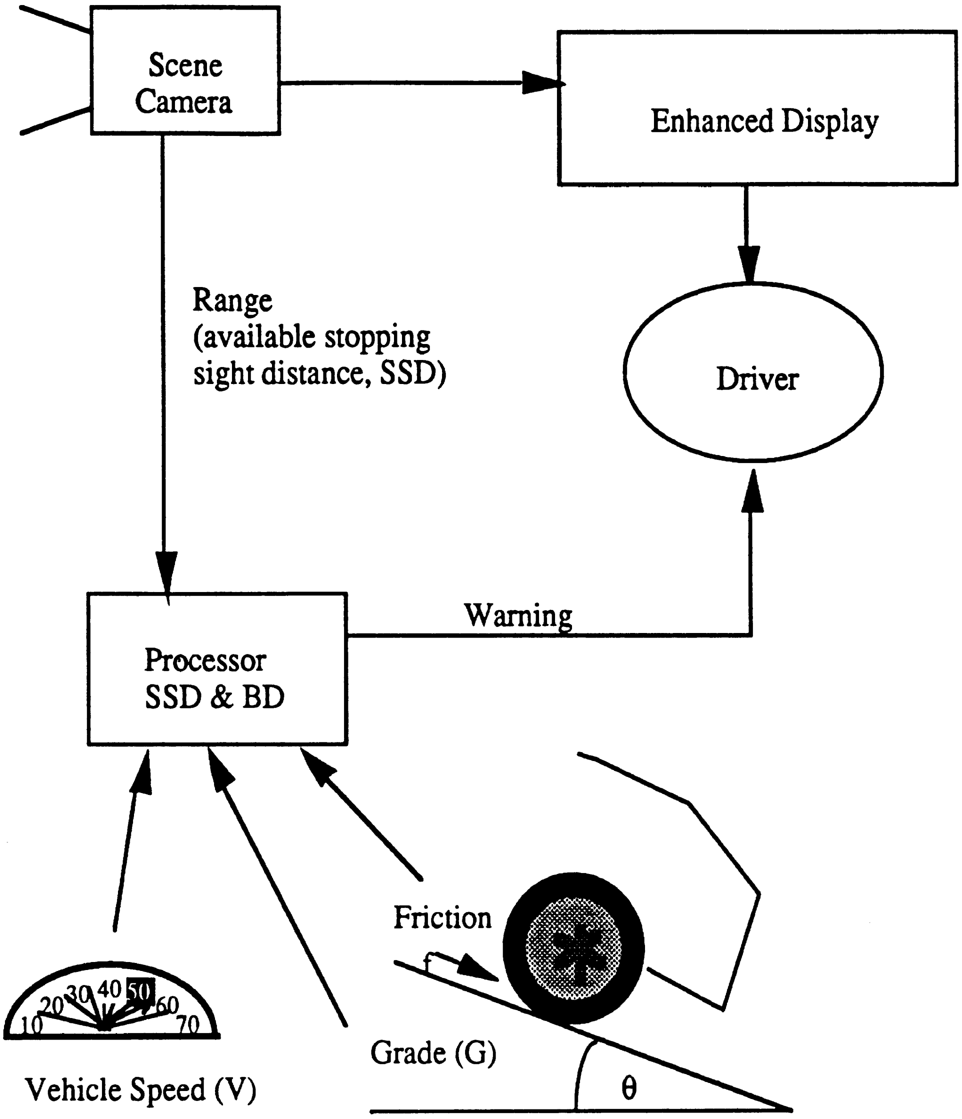
Driver constraint – The driver's reaction time is 2.0 s (R_t).

Functional requirement goals for the sensors and processing unit

Processing time (P_t) – The system will display and update the scene with a processing delay of 0.06 s. The monitor refresh rate will be 30 times per second. The advisable speed would be calculated at this time and projected on the speedometer; if the current speed was greater than the advisable speed, the advisory alarm would sound. Figure 20 gives a flow chart of the processor input and response.

Sensor range – Given the constraints above, the minimum sensor range can be calculated. The total reaction time is the driver recognition and response time (2.0 s) plus the processing delay time (0.06 s). The product of this total time and the vehicle velocity (2.06 s * V) gives the distance traveled before any corrective reaction has been started.

Environmental penetration – If possible, rain, snow, darkness, ice, etc.



Braking Distance (BD) = 2.06V + V ^{2}/(2g(f+G))

Figure 20. Visibility enhancement processor input and response.

Equipment Needed

- Infrared (or other non-visual light) system for producing an image of the driving scene.
- Head-up display (or other system) for displaying the driving scene in a manner that indicates the relationship of traffic conflicts to the vehicle.
- Image range detector (estimates the range at which objects can be discerned in the display).
- Advisory speed display.
- Sensors for vehicle speed, tire/road friction, and grade of roadway.
- Speed warning device for use if the speed is too fast for the discerning range.

Driver impairment

General concept

There is much evidence in the literature identifying driver impairment as one of the contributing causes of vehicle accidents. In this study, driver impairment was found to be a factor in all six of the collision types. Thus, countermeasures for driver impairment apply to all six collision types selected for this study.

Driver impairment is generally caused by fatigue, drowsiness, drugs, alcohol, poor vision, and possibly a handicap by illness and results in the loss of adequate vehicle control.

The state of the driver's condition can be determined by one or a combination of different variables: drivers physiological condition (heart rate, skin resistance, brain wave activity, breath content, eyelid movement, body temperature, etc.), facial movements (eye movement, blinks, and head nods, etc.), steering movements and corrections, and ability to track within a lane.

The driver's values for some subset of these variables could be monitored, relative to distributions for normal alert state. Should the readings indicate an impaired state, an in-vehicle warning could be triggered. Under certain conditions an external vehicular alarm may also be triggered to alert other drivers and law enforcement.

Many systems would be required to monitor all the variables listed above. For example, a video camera for facial expressions, perhaps using infrared light sources for nighttime conditions. Physiological monitoring devices could be used for heart beat and temperature, EEG for brain wave activity, EOG for eye movement, and oximetry and other devices to measure breath content. A steering wheel recorder could measure frequency and magnitude of steering wheel corrections in conjunction with vehicle speed. A video camera could be used to obtain the driver's tracking variability by measuring the vehicles lateral movement relative to the lane boundary lines. There may be problems with the use of any of the systems that require attaching electrodes to the driver's body.

It is also necessary to have reliable information about the relationships of these variables, as well as their interactions, and the state of driver's alertness. Today there is much inquiry into these questions. (See reference 12-15.) The FHWA and the American Trucking Associations Foundation have undertaken research to examine commercial-vehicle driver fatigue, alertness, and alertness-enhancing measures. Another FHWA program is developing an improved highway lane-positioning monitor. The NHTSA has a program in Driver Status and Performance Monitoring. The results of these and other such programs will surely lead to the development of sophisticated driver impairment countermeasures.

Today the most extensively tested and probably easiest to incorporate driver impairment countermeasure would measure the steering characteristics and compare them with those of an alert driver. This type of system has been tested as an indicator for both drowsiness and drug impairment.

Countermeasure concept

Research at Nissan has shown that steering correction patterns for the alert state and the nonalert state differ and they have identified them.[14] Alert state steering-correction patterns are characterized by constant small adjustments, while nonalert state patterns have long periods of nonsteering time followed by large adjustments. These pattern classifications do not apply at speeds below 30 mi/h, during and immediately after turns or the application of brakes.

The proposed countermeasure would monitor the steering wheel corrections, speed, turn signals, and brakes. Whenever the logic identifies a nonalert pattern, a warning is issued to the driver or to other vehicles.

Presentation to the driver

The presentation is a loud, disturbing audio warning and steering-wheel vibration ("buzz") made whenever a nonalert state driving pattern is detected. If two instances of nonalert state are detected within a short time, an external vehicular alarm goes off to alert other motorists and law enforcement. (Perhaps turning on the flashers could be part of the presentation when erratic steering is detected.)

Sensing the driving situation

The device would continuously monitor the steering-wheel correction frequency for 10 s intervals during relatively straight sections of road. Curves would be recognized by prolonged steering angles of more than 20 deg. 10 s after finishing a curve, monitoring would begin again. The application of brakes and turn signals would also be monitored. The steering-pattern recognition logic would not apply during the application of brakes, turn signal, or 10 s following an application. Vehicle speed would be incorporated into the measure. The pattern recognition function would be on when the vehicle speed is over 30 mi/h. (See figure 21.)

While some tests have been carried out in simulators and some actual road tests have been made, a more extensive data base would have to be developed to determine how many 10 s period violations would result in an internal alarm and under what conditions an external alarm should be sounded.

Equipment needed

- Steering wheel angle sensor.
- Brake actuation sensor.
- Vehicle speed sensor.
- Processor for controlling warning based upon state of steering activity, vehicle speed, and brakes.
- Audible warning device.
- Flasher control and device for turning on the flashers.

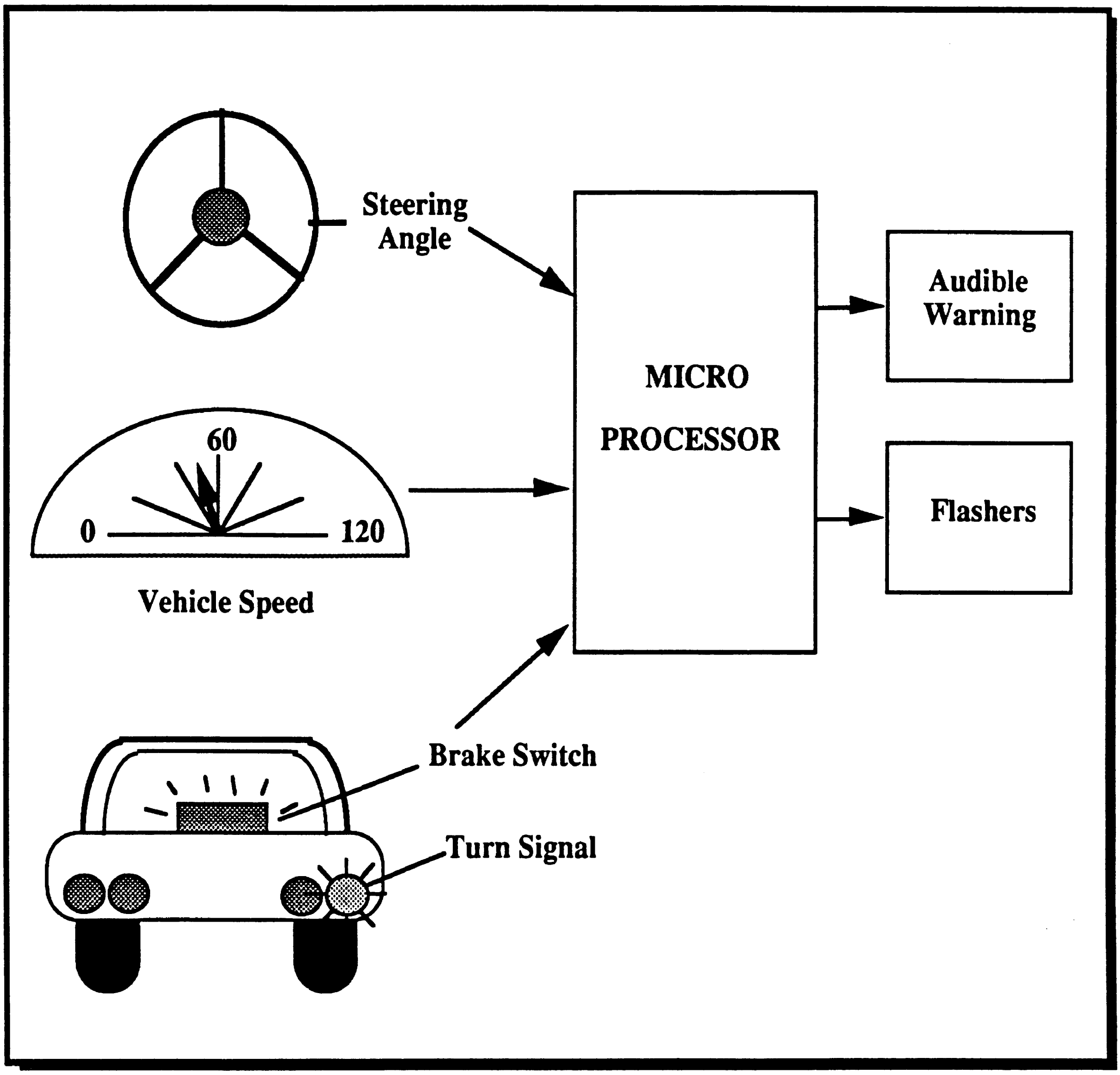


Figure 21. Evaluation and response of driver impairment.

Friction/ice detection and warning systems (vehicle based system)

General concept

Tire-to-road friction is an important factor in vehicle control. Without adequate friction, the tires cannot produce the forces needed to control the vehicle. The envisioned system would be an on-board sensor and processor that would calculate and display an advisory speed. This system would be most useful when there are temperature and humidity changes that affect the road surface and less effective in areas of dramatic friction change. This countermeasure is relevant in run-off-road, vehicle strikes pedestrian/cyclist/animal, rear-end, and head-on collisions.

Presentation to the driver

The driver will see an advisory speed highlighted on the speedometer. This advisory will let the driver know which speed is appropriate given the road conditions. An alarm would also be incorporated to alert the driver that the current velocity does not allow for adequate maneuvering distance. Figure 22 shows the location of the warning devices.

Sensing of the driving situation

The information needed to calculate the safe speed for the road includes the road-stopping-sight distance, the superelevation, and the friction characteristics. An infrared or sonar system will be used to determine the maximum sight distance available. A sensor would be used to determine the grade. A frictional-characteristics sensor would provide the information on the friction at the road surface. The advisory speed would be calculated using the infrared system, reaction time constraints, and friction information, and then be displayed on the speedometer. The speed advisory alarm would be an audio warning when the driver's speed exceeded that advised speed. The driver will be able to independently turn each system on or off depending on its necessity.

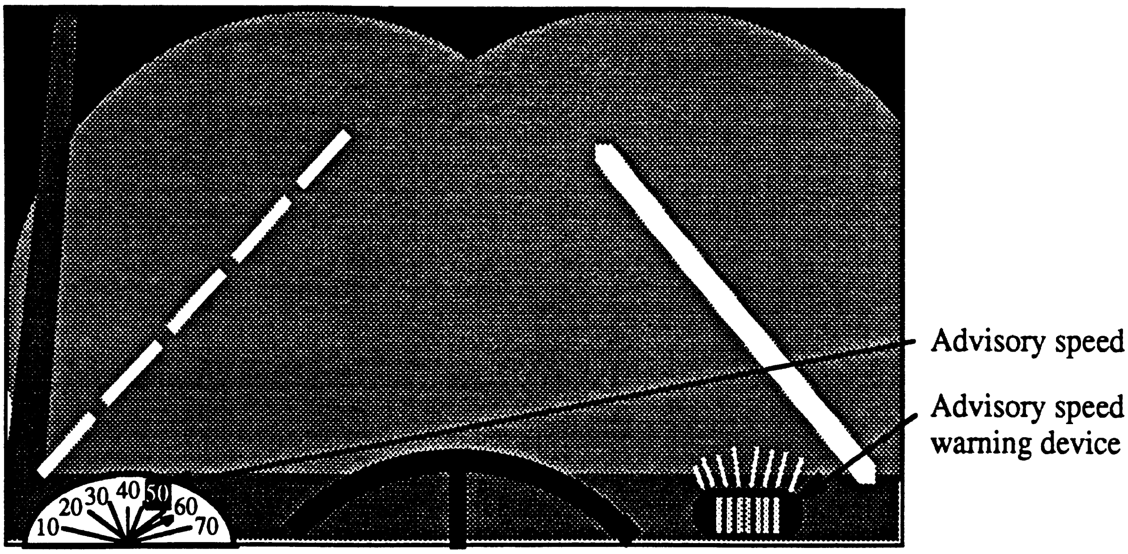
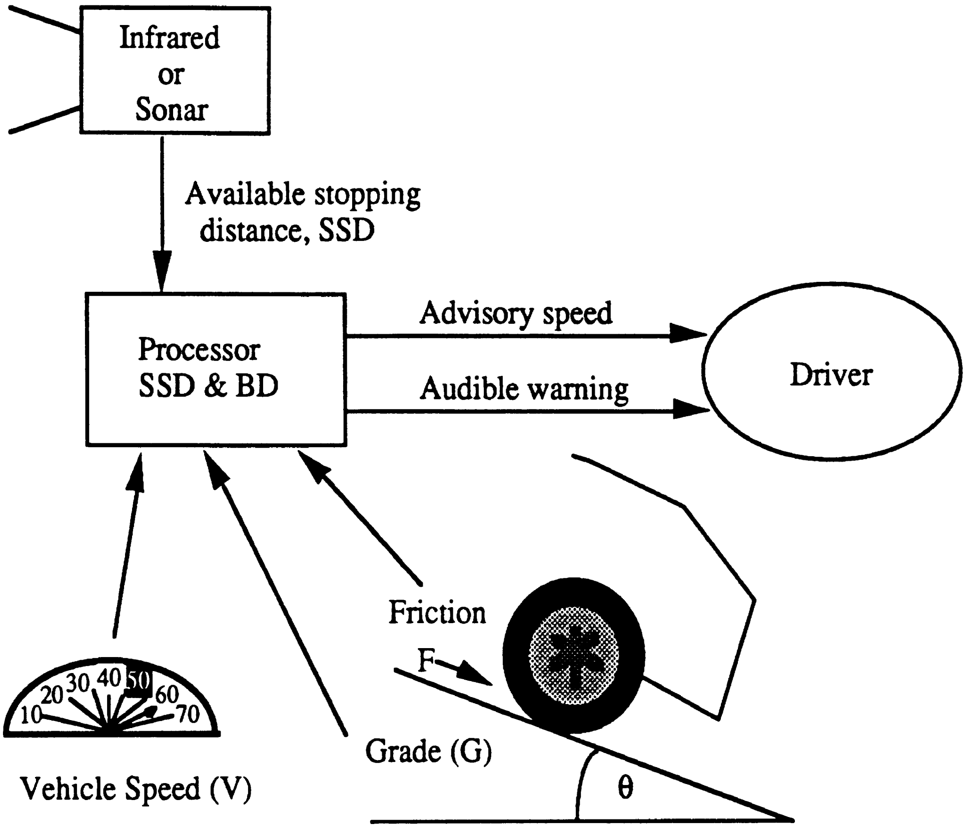


Figure 22. Advisory speed warning devices.



$$\text{Braking distance (BD)} = 2.00V + \frac{V^2}{(2g(F+G))}$$

Figure 23. Surface evaluation and processor response.

Performance and functional specifications

For this particular scenario, the system will have to determine a speed that provides enough time for the driver to slow the vehicle to a stop before reaching a stationary object The equation for the distance needed is:

$$D = R_tV + V^2/(2fg)$$

Where:

D is distance needed to stop for a stationary object

R_t is reaction time of driver

V is velocity of vehicle in ft/s

f is a coefficient that is the sum of the friction between tires and roadway and the grade

g is 32.2 ft/s^2

The maximum sight distance available can be determined by the sensors. The reaction time can be set to 2 s. A value for f can be obtained from either direct measurement or an estimate from the velocity and some of the other variables that can be sensed, i.e., temperature, wetness of road, some surface characteristics, etc. It is assumed that we can measure the grade of the roadway from within the vehicle. To determine a velocity ($V\mu$) necessary when given a certain friction coefficient (μ), we can rewrite the above equation using the quadratic equation to solve for $V\mu$:

$$V\mu = -R_t\mu g + ((R_t\mu g)^2 + 2\mu gD)^{1/2}$$

As an example, we can substitute 2 s for the response time, use a μ of 0.0625 (2 ft/s^2, a very low friction level), and an R of 600 ft to have the following result:

$$V\mu = -4 + (16 + 2400)^{1/2} \approx 45.15 \text{ ft/s} \qquad \text{[about 30 mi/h (48.3 km/h)]}$$

Functional requirements and goals for the sensors and processing unit

There would be a processing time delay of 0.06 s. The advisable speed would be calculated during this time and projected on the speedometer; if the current speed was greater than the advisable speed, the advisory alarm would sound. Figure 23 gives a flow chart of the processor input and response.

Equipment needed

- Infrared or sonar detection system for determining sight distance.
- Advisory speed display.
- Sensors for vehicle speed, tire/road friction, grade of roadway.
- Speed warning device for use if speed indicates driving faster than appropriate for the discerning range.

Friction/ice detection and warning systems (roadway-mounted system)

General concept

Tire-to-road friction is an important factor in vehicle control. Without adequate friction, the tires cannot produce the forces needed to control the vehicle. Drivers must slow down before the friction level changes on a road, in order to have adequate stopping distance. The envisioned system would calculate and display an advisory speed far enough in advance that the driver has time to slow down before reaching the lower-friction road surface. This system would be used in areas that already have signs warning of "slippery when wet" or "bridge may be icy." This countermeasure is relevant in run-off-road, vehicle strikes pedestrian/cyclist/animal, rear-end, and head-on collisions.

Presentation to the driver

The driver will see a roadside display similar to an advisory speed sign for curves (see figure 24). The sign will be illuminated with a dynamic speed advisory. This advisory will let the driver know which speed is appropriate given the road conditions.

Sensing of the driving situation

This system would be used in areas that already have signs warning of "slippery when wet" or "bridge may be icy." These signs imply that the area of concern is distinct from the rest of the road. Information about the site, such as the grade and stopping sight distance would have to be known.

Sensors would be used for obtaining a value for the road friction. They could either use some type of direct measurement system or sense temperature and humidity. The friction coefficient would be a function of the variables sensed, road surface characteristics, and the grade (the last two would be constant for a given situation). A processor calculates the advisory speed using the friction coefficient. This information is then sent to the roadside sign through wiring or local communications transmitters and receivers between the processor and the sign.

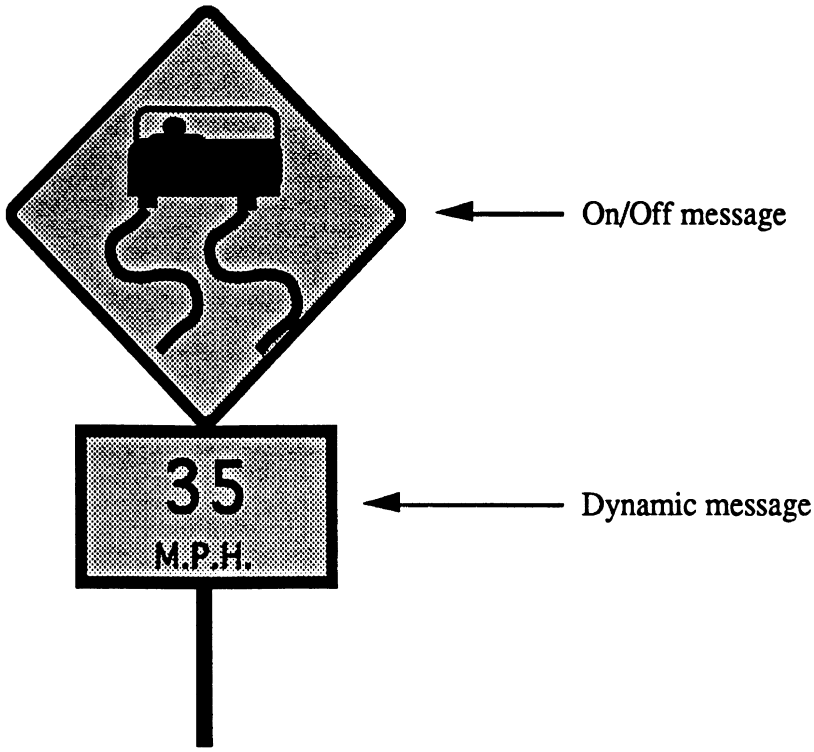


Figure 24. Slippery and advisory speed signs.

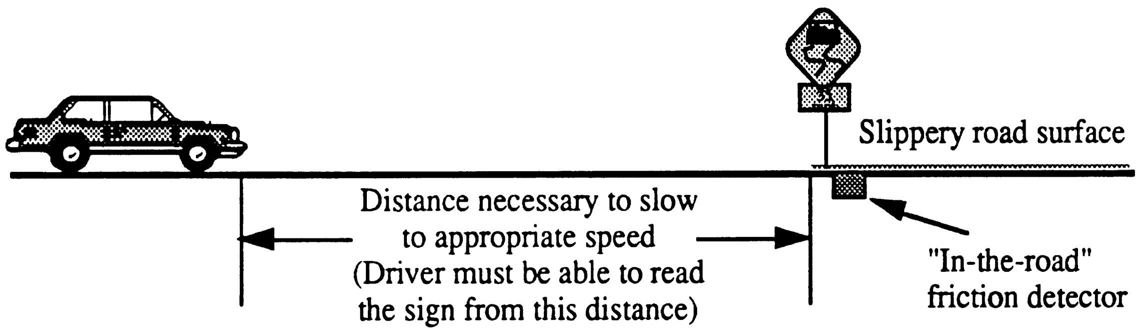


Figure 25. Road layout with an in-the-road friction detector.

Performance and functional specifications

For this particular scenario the system will have to determine a speed that provides enough time for the driver to slow the vehicle to a stop before reaching a pedestrian, animal, or object. Roads are designed so that the minimum sight distance is greater than or equal to the distance needed to come to a complete stop for a stationary object in the road. The distance (R) needed to stop for a stationary object is:

$$R = t_r V + V^2/(2fg)$$

Where:

t_r is reaction time of driver

V is velocity of vehicle in ft/s

f is the coefficient of friction between tires and roadway

g is 32.2 ft/s^2

For a given road with a specific speed limit, we can treat R as a constant. To determine the velocity ($V\mu$) necessary when given a certain friction coefficient (μ) we can rewrite the above equation using the quadratic equation to solve for $V\mu$:

$$V\mu = -t_r\mu g + ((t_r\mu g)^2 + 2\mu gR)^{1/2}$$

As an example, we can substitute 2 s for the response time, use a μ of 0.0625 g (2 ft/s^2, a very low friction level), and an R of 600 ft to have the following result:

$$V\mu = -4 + (16 + 2400)^{1/2} \approx 45.15 \text{ ft/s} \qquad \text{[about 30 mi/h (48.3 km/h)]}$$

The driver must see the advisory speed sign far enough away to be able to slow down to the advisory speed before the change in the road surface. The equation for this distance, D is:

$$D = t_r V + B_d$$

Where:

t_r is reaction time of driver

V is velocity of vehicle in ft/s

B_d is the distance needed to decelerate from current speed to worst-case speed.

(To a rough approximation, $B_d \approx V^2/(2(0.3g))$.)

The distance between the visibility of the sign and the change in the road surface must be greater than or equal to D (see figure 25). The sign may have to be located forward of the different road surface to accommodate this distance. Because the advisory speed would change relatively slowly, we would not foresee a problem with the sign being forward of the point where friction changes.

Equipment needed

- Friction detector installed in the road.
- Processor for calculating speed advisories as well as slipperiness messages.
- Wiring or local communications transmitters and receivers between friction detector, processors, and display.
- Advisory speed sign with dynamic speed display.

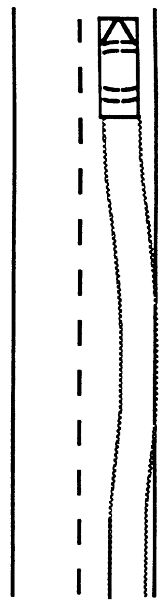


Figure 26. Run-off-road correction.

Lateral lane-edge detection warning and steering correction

General concept

This countermeasure is designed to help prevent run-off-road type accidents. Using active-safety technology, if the vehicle drifts over near the lane boundary, an audio and visual alarm warn that a lane correction is necessary. If the driver fails to correct the vehicle's direction or override the warning, the system would then apply a limited torque steering wheel correction to re-position the vehicle toward the center of the lane. This countermeasure is not designed as a vehicle guidance system, and in situations where the road curves substantially, the system's rate of correction may not be sufficient to keep the vehicle on the road.

Presentation to the driver

Nested in the dashboard of the vehicle among the existing warning lights will be an additional red warning light that is illuminated in conjunction with an audio warning to tell the driver that he is within a preprogrammed distance of the lane edge. If the driver fails to correct the vehicle's lane position within a predetermined time or distance requirement, or fails to disable the system, then an automatic steering correction is applied to the steering system. The level of torque applied to the steering system will be sensitive to the driver's restraining torque allowing the driver to override the automatic maneuver. One possible method of overriding a warning is for the driver to have his turn signal on. This would disable the system and allow the driver to intentionally cross the lane boundary without the distraction of a warning.

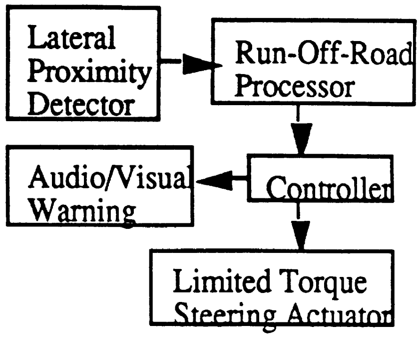


Figure 27. Lane-edge detection - flow diagram.

Sensing of the driving situation

The primary element of the countermeasure system described above is the equipment to detect and measure the distance to the lane edge. This lateral distance (L) is a relatively short distance ranging from 0 to 3 ft. Ideally, the system will be able to identify the road edge from some built-in physical property of the road edge. A cooperative feature incorporated into the road edge is expected to be part of the system. When the vehicle is within 1 ft of the lane edge, the warnings are activated. If the driver immediately corrects the position of the vehicle, then the warnings stop. An automatic swerving maneuver to reposition the vehicle is applied to the steering system after 2.0 s elapse or lateral distance to the lane boundary reaches 0.0 ft. The maneuver would be defined to change the lateral position of the vehicle by 2 ft. The maximum lateral acceleration anticipated is no more than 4 ft/s^2 – well within the normal driving range. The time to complete the lateral displacement described above is approximately 1.7 s. After the maneuver the system would reevaluate the vehicle's position and apply another 2 ft correction if necessary. If after the correction the vehicle is more than 1 ft away from the lane edge the warnings stop and the system resets. It is envisioned that the lane edge detector and its associated processor have a computation frequency of 20 Hz.

Equipment needed

- Lane edge sensor for near - lateral proximity [3 ft (0.9 m) or less].
- A means of enhancing the lane boundary for the sensor.
- Processor for: (1) predicting running-off-the-road based on distances to the lane edge and (2) generating warnings and steering commands.
- Warning device for indicating that the vehicle is too close to the edge of the road.
- Steering actuator that can apply limited steering torques for swerving. (These torques might be limited to no more than 2 or 3 ft-lb, measured at the steering wheel.)

Lane-edge detection warning and steering correction with lateral and longitudinal preview

General concept

This countermeasure is designed to help prevent run-off-road type accidents. Using active-safety technology, as a driver inadvertently allows his vehicle to drift over near the lane boundary, an audio and visual alarm warn that a lane correction is necessary. If the driver fails to correct the vehicle's direction or override the warning, the system would then apply a limited torque steering wheel correction to change the vehicle's heading in an attempt to keep the vehicle on the road. This countermeasure is not designed as a vehicle guidance system, and in situations where the road curves substantially, the systems rate of correction may not be sufficient to keep the vehicle on the road.

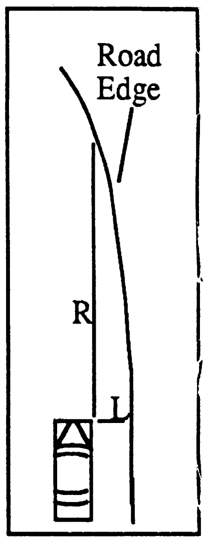


Figure 28. Run-off-road correction.

Presentation to the driver

Nested in the dashboard of the vehicle among the existing warning lights will be an additional red warning light that is illuminated in conjunction with an audio warning to tell the driver that he is within a preprogrammed distance of the lane edge. If the driver fails to correct the vehicle's lane position within a predetermined time or distance requirement, then an automatic steering correction is applied to the steering system. The level of torque applied to the steering system will be sensitive to the driver's restraining torque allowing the driver to override the automatic maneuver. One possible method of overriding a warning is for the driver to have his turn signal on. This would disable the system and allow the driver to intentionally cross the lane boundary without the distraction of a warning.

Sensing the driving situation

The following features of the driving scenario are sensed and communicated to the controlling system by advanced technology: (1) location of the lane edge with respect to the vehicle—both laterally (L) and longitudinally (R) and (2) vehicle forward speed (V). The vehicle is to perform a heading change maneuver to redirect the vehicle to a path that is approximately parallel to the road edge. In order to define the performance and functional specifications for the active-safety system described above, certain vehicle, driver, and system constraints must be defined. For the vehicle, these constraints are: (1) the vehicle's lateral acceleration will not exceed 4.0 ft/s^2 and (2) yaw rate corrections made by the system will not be greater than 0.1 rad/s. These constraints correspond to maneuvers that would be classified as normal driving. The maximum range of the system may be estimated by choosing a maximum speed and a driver response time—say 100 ft/s and 1 s—plus 50 ft to maneuver. Then the maximum R is 150 ft. The maximum L is 3 ft for a heading correction that can be made in about 0.5 s without exceeding a yaw rate of 0.1 rad./s. That is, the ratio of L/R = 1/50 or more for the alarm to sound. The drift limit is to be L = 1 ft. If the vehicle is closer than 1 ft from the edge, sound the alarm and add a swerving (to the left) type signal to the steering torque. (This signal will last 1.25 s.) If at the end of the steering torque signal the problem is not corrected, the alarm remains on.

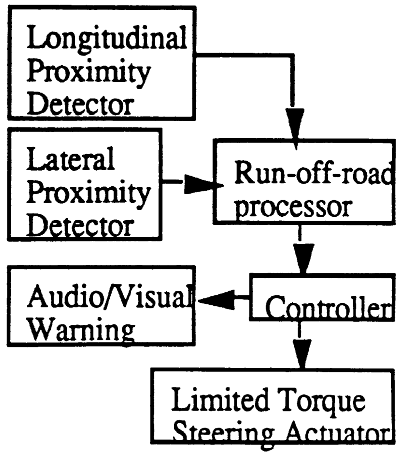


Figure 29. Lane-edge detection - flow diagram.

Equipment needed

- Longitudinal and lateral lane-edge sensors.
- A means of enhancing the lane boundary for the sensor.
- Processor for: (1) predicting running-off-the-road based on distances to the lane edge and (2) generating warnings and steering commands.
- Warning device for indicating that the vehicle is too close to the edge of the road.
- Steering actuator that can apply limited steering torque for swerving. (This torque might be limited to no more than 2 or 3 ft-lb, measured at the steering wheel.)

Dynamic horizontal-curve speed advisory and control

General concept

The objective of this system is to get drivers to negotiate horizontal curves at speeds safe for the current conditions. Accordingly, it is a countermeasure applicable to single vehicle run-off-the-road accidents.

The safe speed for the curve at any time is determined from the radius of the curve, the superelevation, and the frictional characteristics of the road surface. The advisory speed is conveyed to the driver by a roadside changeable message sign and/or an in-vehicle display at a distance sufficiently ahead of the curve to allow the driver to adjust the vehicle speed from the traveling speed to the advisory speed. If control intervention is involved, the brakes are applied traveling speed to the advisory speed. If control intervention is involved, the brakes are applied at a 0.1 g deceleration level starting at the location of the display until the advisory speed is reached.

Three versions of this countermeasure are presented here:

Version 1 consists of the roadside display of the curve-ahead warning with dynamic speed advisory changeable-message sign.

Version 2 incorporates a roadside transponder that sends out a curve-ahead warning and speed-advisory to on-board vehicle receivers. It is likely that only a portion of the vehicle fleet will have the necessary on-board equipment. Thus, version 2 consists of version 1 plus the transponder and on-board equipment on some portion of the vehicle fleet. It can be argued that even if the portion of the fleet with the necessary on-board displays is small, the cost of the added roadside transponder equipment is justified in that it contributes to the safety of all highway users.

Version 3 is version 2 plus control intervention on a portion of the vehicle fleet. The control intervention system applies brakes to bring the vehicle to the advisory speed if the driver is not slowing the vehicle.

Presentation to driver

Version 1 – roadside sign.

The dynamic curve-ahead sign with advisory speed is similar to the current curve-ahead/advisory speed sign. The advisory speed sign, however, is a changeable-message sign that displays the speed advised for the current conditions. In addition to the advisory speed, the message "slippery" is displayed if the surface is slippery. The elements in the changeable message sign are coated with reflective materials such that they can be seen at night. (See figure 30.)

Version 2 – roadside sign and on-board display

In addition to the roadside sign described above, drivers of vehicles equipped with on-board equipment are informed, via a dashboard display, of an upcoming horizontal curve, given the current advisory speed for that curve, and informed if deceleration is needed. (See figure 31.)

Version 3 – on-board display and control intervention

In addition to the roadside and on-board systems described above, vehicles equipped with control intervention systems will start decelerating if the vehicle is traveling above the advisory speed for the curve and the driver has not initiated deceleration at the roadside sign. The car will decelerate until it reaches the advisory speed.

Sensing the situation

Information needed to calculate the safe speed for the curve includes the radius, superelevation, and friction characteristics of the road surface. The radius and superelevation of the horizontal curve are constant and thus known once measured. A frictional-characteristics sensor provides the information on the friction at the road surface. (See figures 32 and 33.)

A processor calculates the advisory speed and determines if the friction characteristics indicate a slippery surface. This information is sent to the roadside sign and to the transponder. (See figure 34.)

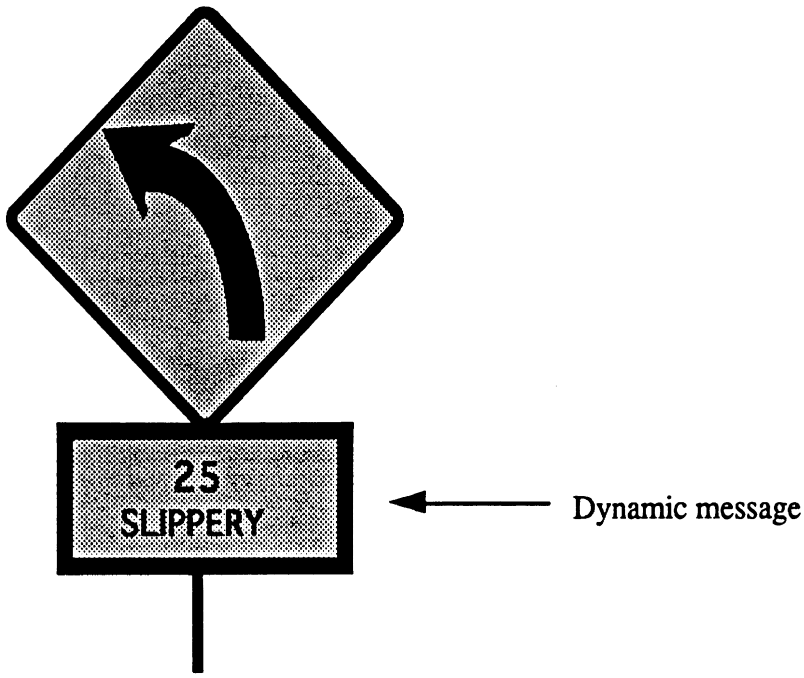


Figure 30. Presentation to the driver, roadside sign.

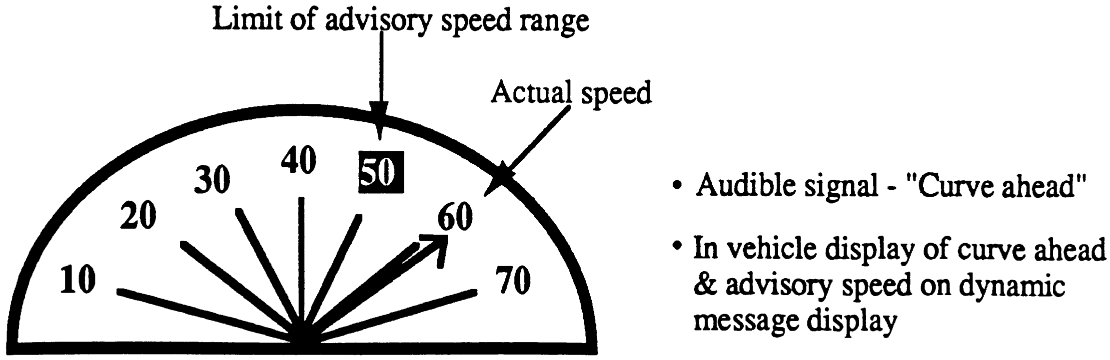
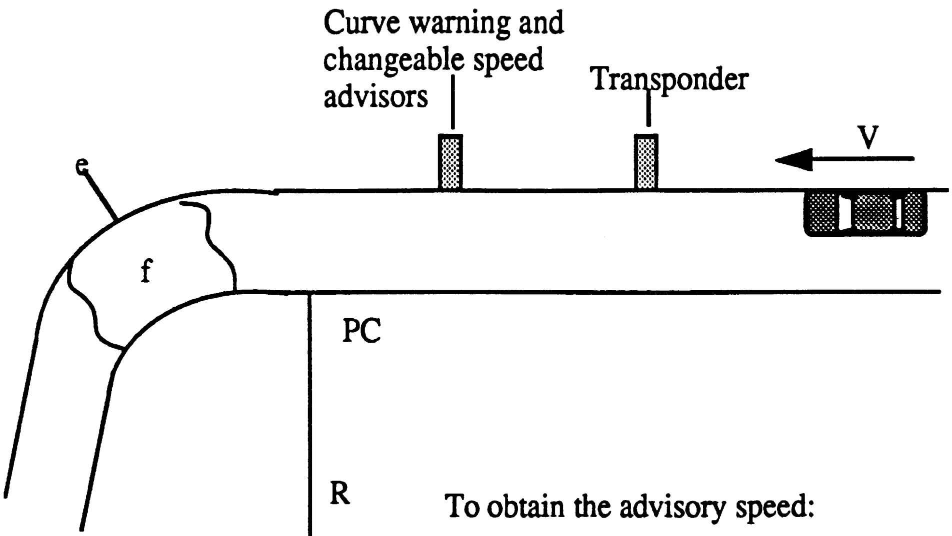


Figure 31. In-vehicle advisory speed display.



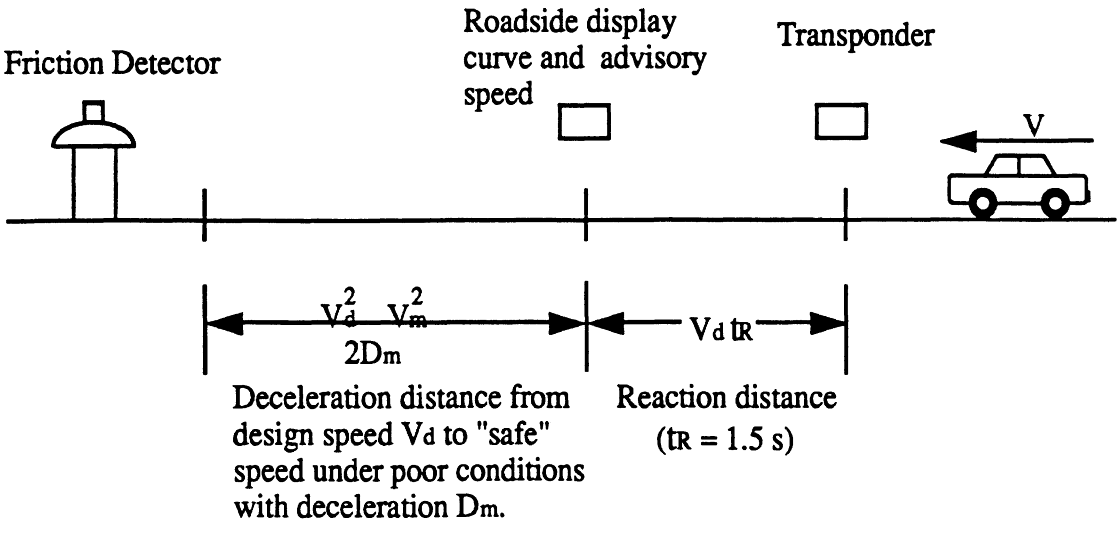
To obtain the advisory speed:

$$\left[\frac{V_A^2}{Rg} - e\right] = f$$

$$\Rightarrow \quad V_A = \sqrt{(e + f)Rg}$$

f = Available friction
R = Radius
e = Super-elevation
V_A = Advisory speed
g = Gravitational acceleration constant
PC = Point of curvature

Figure 32. Advisory speed calculated for a horizontal curve.



V_d = Design speed (function of road)
t_R = Reaction time (assume 1.5 s)
V_m = Advisory speed for poor marginal conditions
D_m = Deceleration rate for poor marginal conditions

} calculated from very low friction conditions $f \approx 0.1$

Figure 33. Roadside location of the advisory and control system.

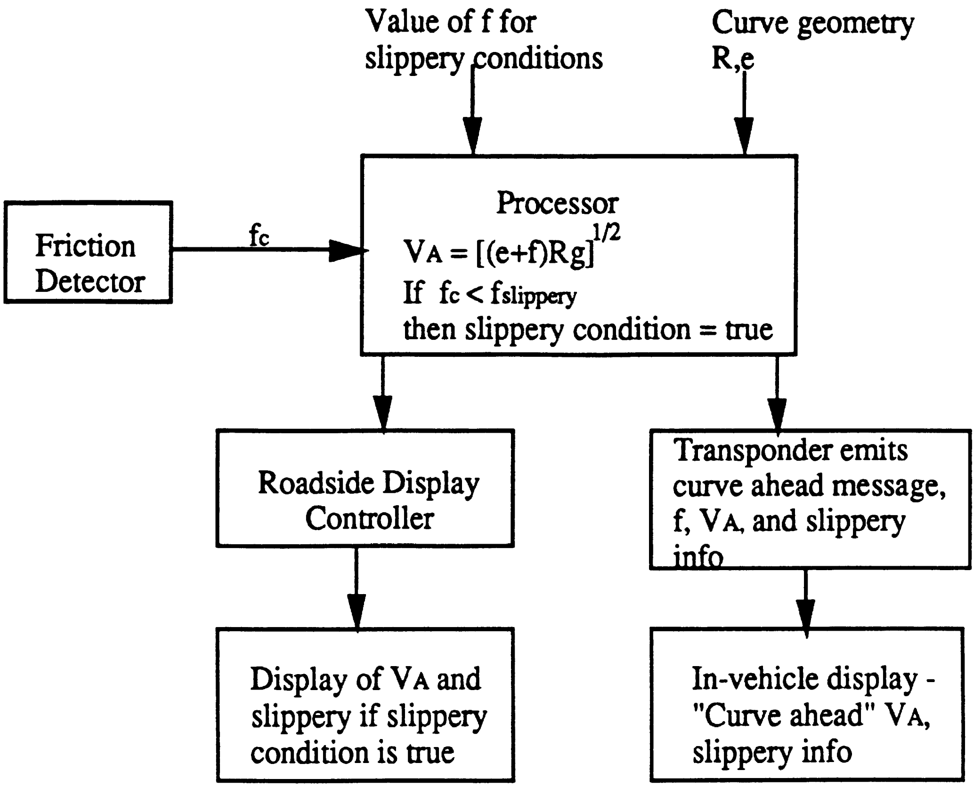


Figure 34. Roadside sign and on-board display vehicle controller.

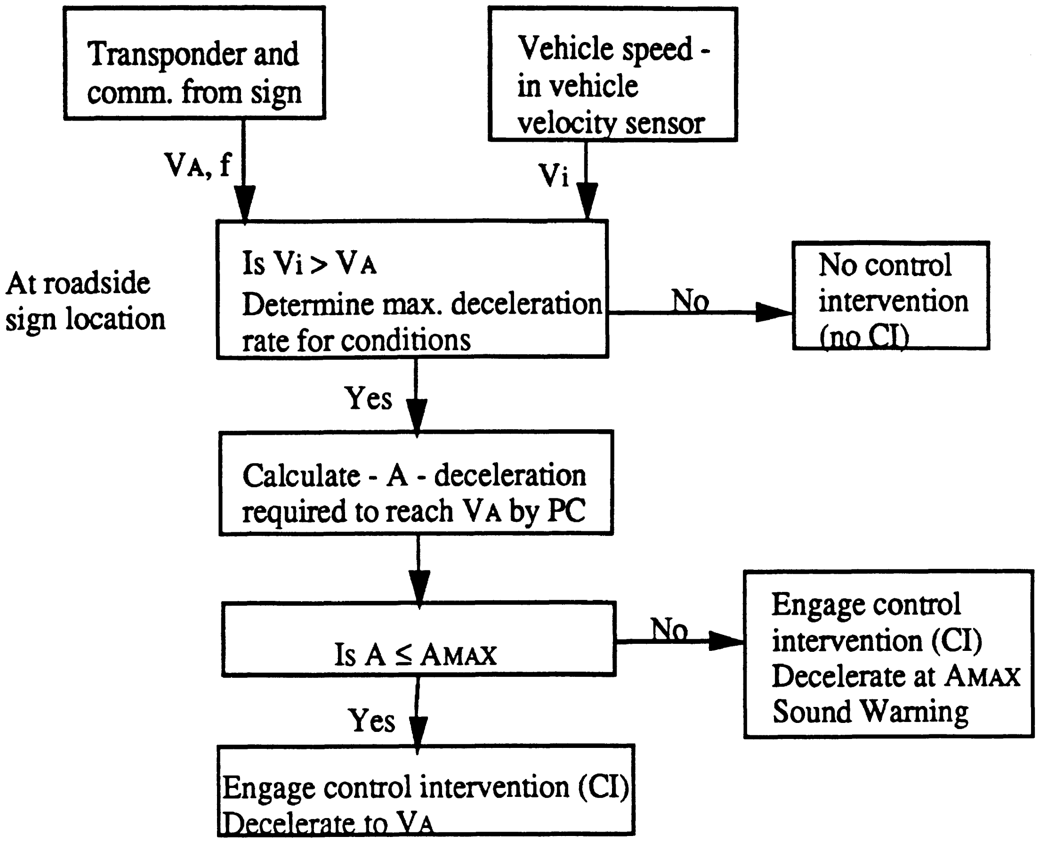


Figure 35. On-board display and control intervention (CI) vehicle controller.

In vehicles with control intervention systems, the speed of the vehicle is sensed as the vehicle passes the transponder. An on-board processor determines if the vehicle speed is greater than the advisory speed, senses if the vehicle is decelerating, and determines if the brakes should be automatically engaged. If yes, then the brakes are engaged at a gentle deceleration of .1 g to bring the vehicle to the advisory speed before the beginning of the curve. (See figure 35.)

Equipment needed

- Sensors
  Road-based friction detector
  On-vehicle speed sensor.

- Processors
  Calculator for advisory speed
  Decision if conditions are slippery
  On-board decision if control intervention is to be engaged.

- Communication Devices
  Transponders

Wiring or local communications transmitters
Receivers between friction detector, processors
Display and transponders.

- Displays
  Changeable message roadside warning sign with speed advisory
  In-vehicle advisory speed display
  In-vehicle warning of curve ahead
  In-vehicle warning of speed reduction advised.

- Controller Units
  Control-intervention unit for setting vehicle speed to the advisory speed.

<u>Longitudinal control for objects in the roadway</u>

General concept

This countermeasure is aimed at reducing the number of single-vehicle on-road crashes. These include collisions with objects on the road or with pedestrians or animals. In addition, this countermeasure will be applicable in reducing crashes with stopped vehicles.

The concept is based on detecting fixed or slow-moving obstacles at sufficient distance to allow the vehicle to stop before reaching the obstacle. If a warning is to be issued, there is a provision for driver reaction time. Control intervention (CI) is used when the range at which the warning is initiated is shorter than that necessary for the driver to react, even if a mild deceleration is employed.

Presentation to driver

A display on the speedometer informs the driver of the maximum speed at which the longitudinal control system is effective.

Let's assume that an object has been detected some distance ahead, in the path of the vehicle. If this distance is sufficient for the driver to react and stop before reaching the location of the object, a warning icon or an image of the object itself appears on a head-up display on the windshield along with an audible signal.

If the warned driver does not slow down the vehicle or change direction, and the object does not go away, braking is initiated by a control intervention system and the vehicle stops before reaching the object.

If the distance to the object is less than that needed for reacting and decelerating to a stop, the brakes are automatically applied at a deceleration rate adequate for the vehicle to stop before reaching the object. A more emphatic audible warning is sounded.

Sensing the driving situation

The system is operational only on straight road segments and is disengaged if the steering wheel is turned. The presence of a stationary or slow-moving object in the lane of travel is detected by a sensor. The distance to the object is also sensed. Note that the distance to the object is not necessarily the maximum range of the sensor. For example, the vehicle may be following another vehicle when it changes lanes, exposing a stalled vehicle, another object in the roadway ahead, or a pedestrian stepping out onto the roadway. (See figure 36.)

The speed of the vehicle, whether it is decelerating, or whether an avoidance maneuver (lateral movement) has been initiated are also sensed.

A processor determines if the warning should go off, if control intervention should engage the brakes, and the deceleration level needed if the brakes are automatically applied.

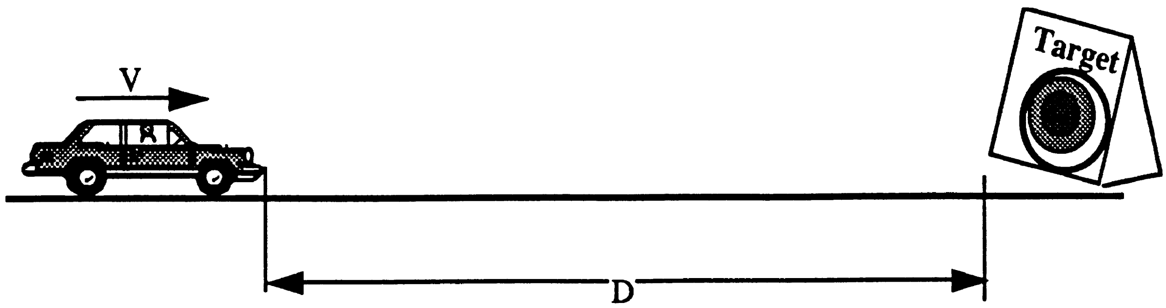
System requirements

The range of the detection sensor has to be equal to or greater than the reaction and braking distance for the speed of travel. Typically this would be the design speed of the roadway.

A version of this system can be conceptualized, in which the maximum speed for the conditions can be determined from the maximum deceleration and the sensor's maximum range. In that case, the maximum achievable deceleration would depend on the friction between the road surface and the tires, and there would be a need to sense this friction. If the vehicle was exceeding this maximum speed, a warning could go off, or the speed could be automatically reduced. (See figure 37.)

Equipment needed

- Sensor for detecting presence and distance to fixed or slow-moving objects in the lane of travel.
- Control intervention, if driver does not apply brakes, changes direction laterally, or the object does not go away.
- Processor for deciding if warning is needed, if control intervention is required and deceleration level.
- Brake actuator to attain selected deceleration.
- Velocity sensor to furnish velocity information to the processor.



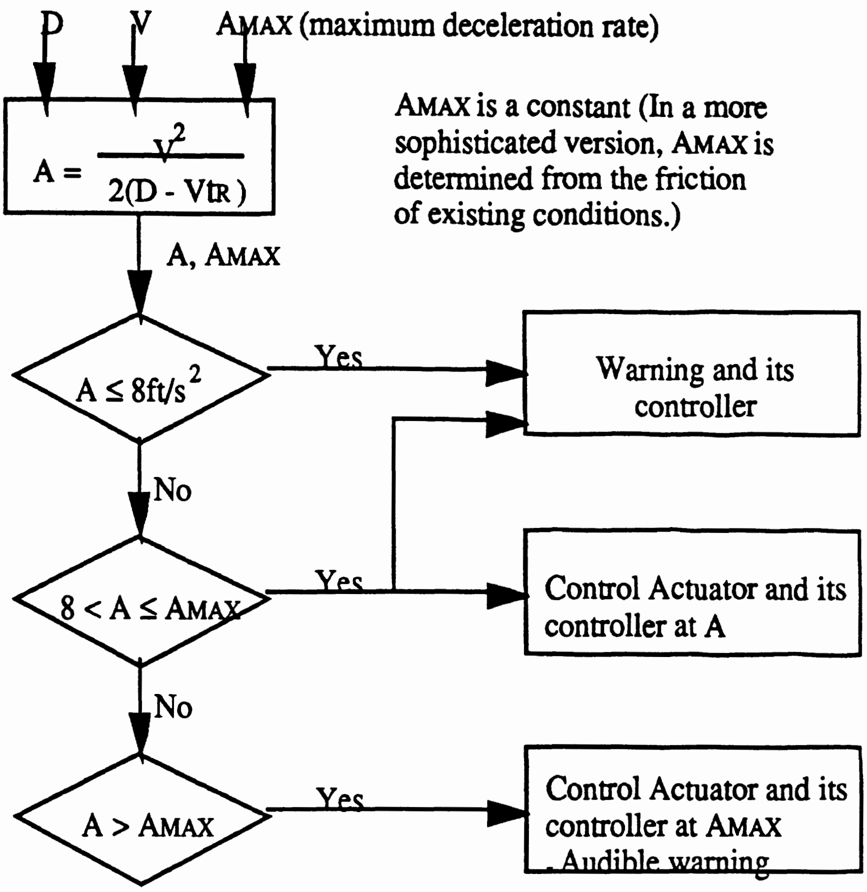
Let :
t_R = Driver reaction time (assume 1.5 s)
A = Deceleration rate
V = Vehicle velocity
D = Distance between vehicle and target
A_{MAX} = Maximum deceleration rate

D and V are sensed — Processor solves for A

$$D = Vt_R + \frac{V^2}{2A}$$

$$A = \frac{V^2}{2(D - Vt_R)}$$

Figure 36. Vehicle deceleration variables.



1 ft = 0.305 m

Figure 37. Longitudinal controller input and response.

Indicators informing drivers of presence of pedestrians at mid-block crosswalks

General concept

This countermeasure addresses pedestrian accidents and is applicable at mid-block crosswalks at locations near schools and at other nonintersection locations where pedestrians are likely to cross. The countermeasure resembles a pedestrian-crossing warning sign but has a yellow indicator light on top of it. The sign is located on each approach to the pedestrian crossing. If pedestrians intending to cross the road are present, the light indicators on top of the signs begin to flash. The lights stay on for the time it takes the pedestrian to cross the road. The intent is to warn the driver that there are pedestrians-crossing or about to cross the roadway. It enhances the present day pedestrian crossing warning sign by upgrading it from a device that warns of likely hazards to one that warns of an observed hazard. It also could replace some mid-block signals with pedestrian buttons. Figure 38 shows a schematic of this concept.

Presentation to pedestrian and driver

Each side of a crosswalk has a special marked area (a pedestrian portal or ped-port) from where the pedestrian is required to begin crossing the road. This area is where the presence of the pedestrian is sensed.

The driver is presented with a pedestrian crossing warning sign that has a yellow indicator light mounted on top of the sign. The indicator light begins to flash when a pedestrian is detected in the ped-port moving toward the street. The indicator light remains on for a preset time based on the time required for a pedestrian to cross the road. The information conveyed to the driver is that pedestrians are either crossing or about to cross the street at the crosswalk and to be on the lookout for them. The sign is placed at a distance, giving the driver adequate time to stop before the crosswalk.

Sensing the situation

A sensor detects the presence of a pedestrian in the ped-port and determines if the pedestrian is moving toward the roadway. If it is sensed that there is a person and that person is moving toward the street, a signal is sent to the pedestrian warning indicator to begin flashing. The indicator remains on for the average time it takes a pedestrian to cross that particular roadway. If another pedestrian is sensed in the ped-port moving toward the street after the first pedestrian has started (but not completed) crossing the street, then the on indicator is reset for another complete crossing cycle. (Perhaps there can be another sensor that determines if there is a pedestrian in the crosswalk.)

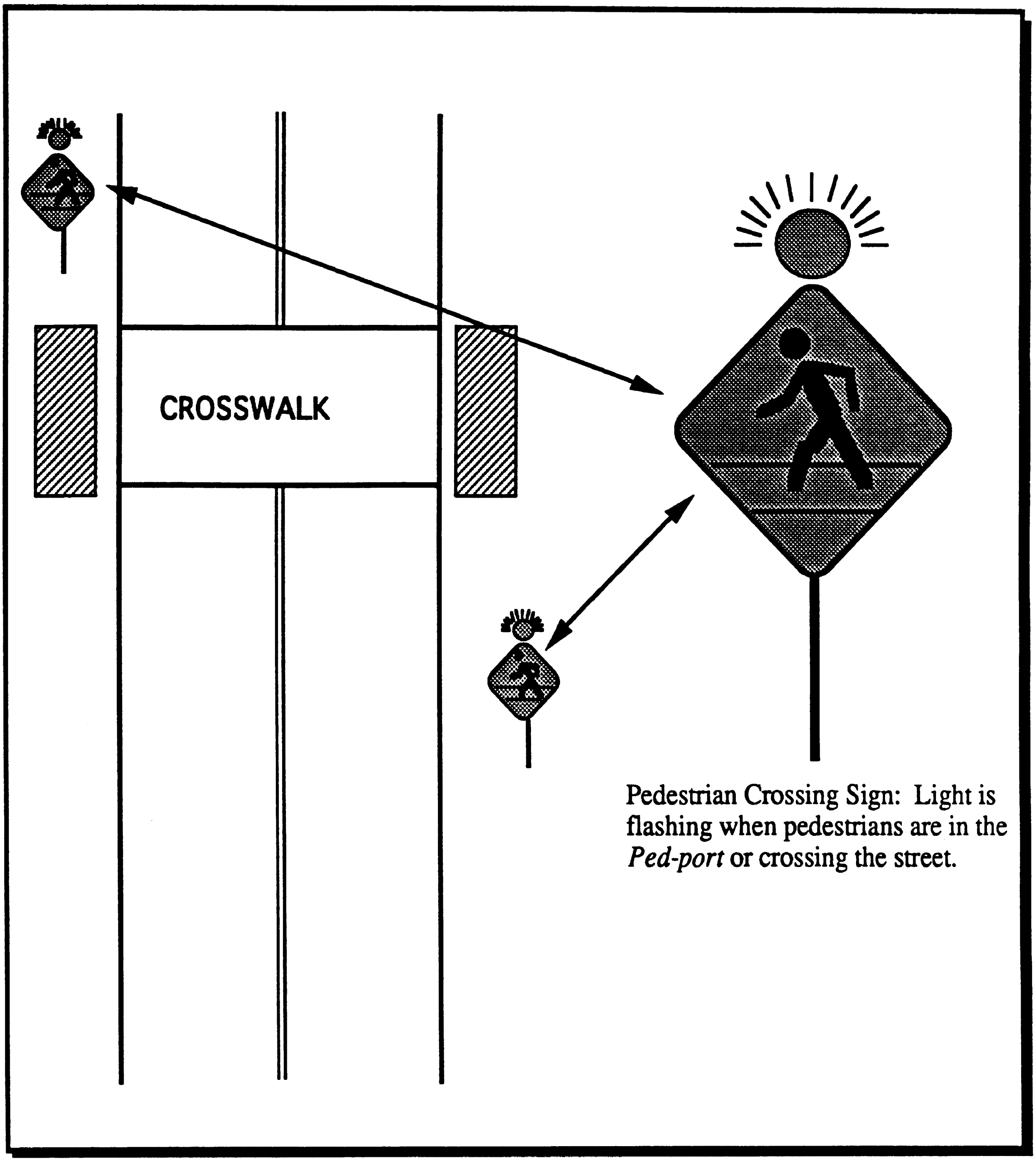


Figure 38. Road diagram of pedestrian crossing.

Performance and functional specifications

The sensors in the ped-port must sense the presence of a person or persons in the ped-port and sense that the direction of movement of at least one of the sensed persons is toward the roadway.

Functional requirements goals for the sensors and processing unit

- Processing time – should be very short - microseconds.
- Environmental penetration – If possible, rain, snow, darkness, ice, etc.

Once the processor determines that a person will be crossing the street, the pedestrian-warning indicator light on the warning sign starts to flash. The time the indicator is on depends on the time needed for a pedestrian to reach and cross the roadway.

The average walking rate for pedestrians crossing streets is 4 ft/s. The rate for elderly pedestrians is about 3 ft/s. Thus, the preset time for the indicator flasher to be on once triggered is:

$$\text{time on} = \text{roadway width (ft)} / 3 \text{ ft/s}$$

The location of the pedestrian-crossing warning sign should be such that the driver has adequate distance to react to the sign and to stop before reaching the crosswalk. This distance depends on the vertical and horizontal alignment of the road and is therefore site specific.

Table 20 gives the minimum distance for the placement of the sign at locations with no vertical or horizontal curvature. A driver reaction time of 1.5 s and a deceleration of 8 ft/s^2 are assumed.

Table 20. Minimum sign distances for given velocities.

Velocity	Min. distance between Sign and Crosswalk	Time on roadway (s) for Different Roadway Widths		
mi/h	ft	30 ft	40 ft	60 ft
20	98	10	13.3	20
25	139	10	13.3	20
30	187	10	13.3	20
35	242	10	13.3	20
40	303	10	13.3	20
45	372	10	13.3	20

1 mi/h = 1.61 km/h
1 ft = 0.305 m

Equipment needed

- Pedestrian sensors.
- Communication from sensors to sign-controller and from controller to lights.
- Sign-controller that turns a flashing light on for long enough to allow the last pedestrian to cross (perhaps this could be augmented with a device that detects whether a pedestrian is in the crosswalk).

A system for headway control, based upon a modified cruise-control

General concept

This countermeasure is designed to help prevent rear-end type accidents and is based on enhancements to existing cruise-control concepts. Stated simply, under specified conditions the control speed used by the cruise-control is changed from the driver-set value to the velocity of the vehicle ahead. A major disadvantage of conventional cruise-control systems occurs when a slower vehicle is encountered from behind. In this situation the driver of the faster vehicle must either disengage the cruise-control or change lanes to avoid a rear-end collision with the slower vehicle. This enhanced system would employ a distance-measuring sensor installed in the front of the vehicle to determine the range to the vehicle ahead. Using this information, along with some other values (range rate, vehicle speed, driver's desired speed, etc.), the system would continually adjust the vehicle's speed to maintain a safe, preset distance between it and the vehicle ahead. When the system no longer senses the presence of the lead vehicle, it returns to normal cruise-control operation and accelerates to the speed set by the driver.

Presentation to the driver

From the driver's point of view the headway control concept would function and look similar to current cruise-control systems. The only exception would be an audio and visual warning to alert the driver in situations where the headway control cannot adjust the vehicle's speed fast enough to maintain preset safety conditions. There will also have to be a way for the driver to periodically change certain system control numbers. One such number is the headway "cushioning": in the vehicle tracking situations, if the combination of range and range rate are such that the cushioning distance cannot be sustained (i.e., the lead vehicle is slowing rapidly), then the system disengages itself and activates the appropriate warning (automatic brake application could also be considered).

Sensing the driving situation

The headway control concept discussed here incorporates a commonly used cruise-control for governing the speed of the vehicle. Without interfering vehicular entities, the system functions as a conventional cruise-control. When interferences are introduced, the system autonomously adapts itself to accommodate the new contingency. No action is required from the driver under these circumstances. In the case of interferences that the system cannot adapt to, it disengages itself and issues a warning to the driver to take control. The general layout that describes the way a cruise-control functions is portrayed in figure 1. The system uses a single control input, that is the cruising speed selected by the driver. By monitoring the error signal between the desired speed and the actual speed of the vehicle, the cruise-control system compensates and changes the throttle signal setting to achieve a zero error.

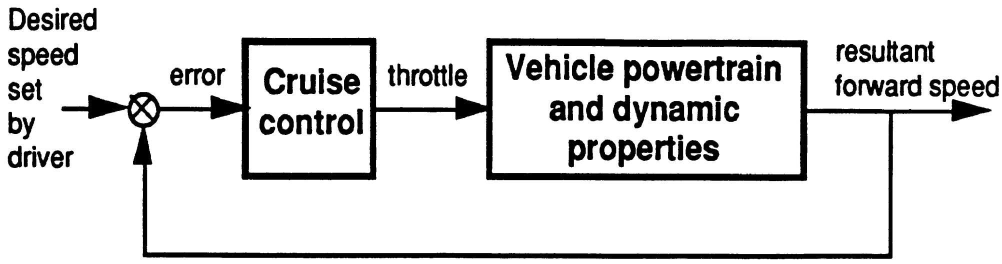


Figure 39. Cruise-control.

In contrast to the cruise-control, the headway control system employs a second input that allows a more autonomous operation, with less driver intervention. Such a system is illustrated in figure 40. A distance measuring sensor installed at the front of the vehicle picks up the range from the vehicle ahead. The rate at which the range changes is also calculated. The headway control unit continuously accepts the range, range rate, present vehicle speed, and driver's desired speed inputs. By combining the range, range rate, and the vehicle speed, the control unit also evaluates the speed of the leading vehicle. "Headway mode" operation is when the control system maintains a constant range from the lead vehicle (the controlling speed is the speed of the leading vehicle). "Cruise mode" operation is when the system functions as a conventional cruise-control (the controlling speed is the speed set by the driver). The system uses a heuristic algorithm to switch between the headway and cruise-control modes, or disengage itself altogether and activate a warning signal if a rear-end collision is imminent.

The concept of this system also allows it to avoid collisions with stationary obstructing objects (parked vehicles or other obstacles). By continuously evaluating the gap and its rate of change between the vehicle and the object ahead (a slower vehicle or any other obstacle), the unit can assess the situation and take appropriate action.

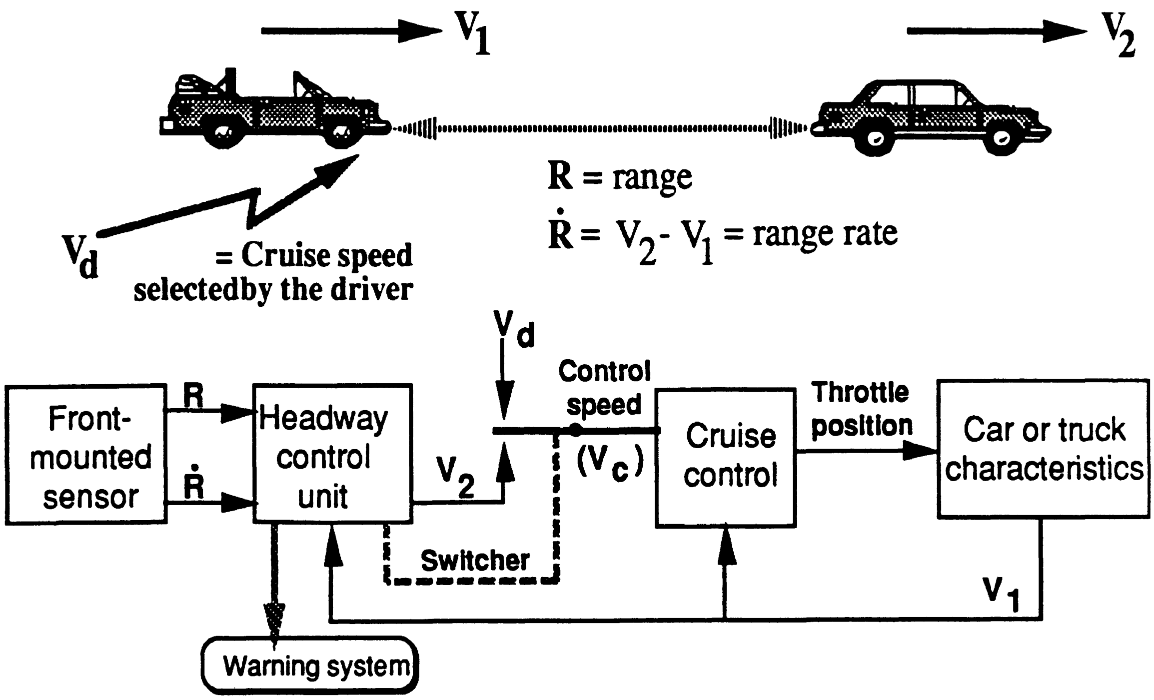


Figure 40. Headway control.

Equipment needed

- Range and range-rate sensor(s).
- Headway control unit (contains logic and processor for determining velocity commands).
- Cruise-control unit that accepts externally generated velocity signals.
- Throttle actuator (may be part of the cruise-control unit).
- Driver preferences panel for time-too-short and distance-too-short settings.
- Driver warning system for indicating when situation needs driver intervention.

<u>Cooperative warning of the presence of oncoming vehicles</u>

General concept

This countermeasure is aimed at reducing the number of head-on collisions by providing drivers with enhanced awareness of the presence of oncoming vehicles on curves with limited sight distance. The envisioned system uses light sensors on posts to detect the presence of oncoming vehicle headlights. These light sensors cause a light, possibly mounted on the same post, to become illuminated when headlights are detected. This light can be seen by vehicles coming the other direction around the curve. This information indicates to drivers that a vehicle is coming. The system is seen as cooperative in that vehicles are expected to have their headlights on. A schematic diagram portraying a hypothetical implementation is given in figure 41.

Presentation to the driver

Lights mounted on posts along the roadside are illuminated to indicate the presence of a vehicle down the road. As a vehicle's headlights reach a post, the light comes on causing a moving line of lights to be visible to oncoming vehicles. These lights inform a vehicle of oncoming traffic before the actual headlights are seen. See figure 41 for a sketch of the situation and in particular, the location of the warning lights.

Sensing the situation

Light sensors will be located on the posts and will detect the illuminated headlights of a vehicle down the road. These sensors will be able to discriminate headlights from other sources of light such as sunlight. (See the discussion of technology in chapter 5.) The posts can be current shoulder-edge reflectors, chevron signs, or posts specially installed for implementing this countermeasure. (See figure 42.)

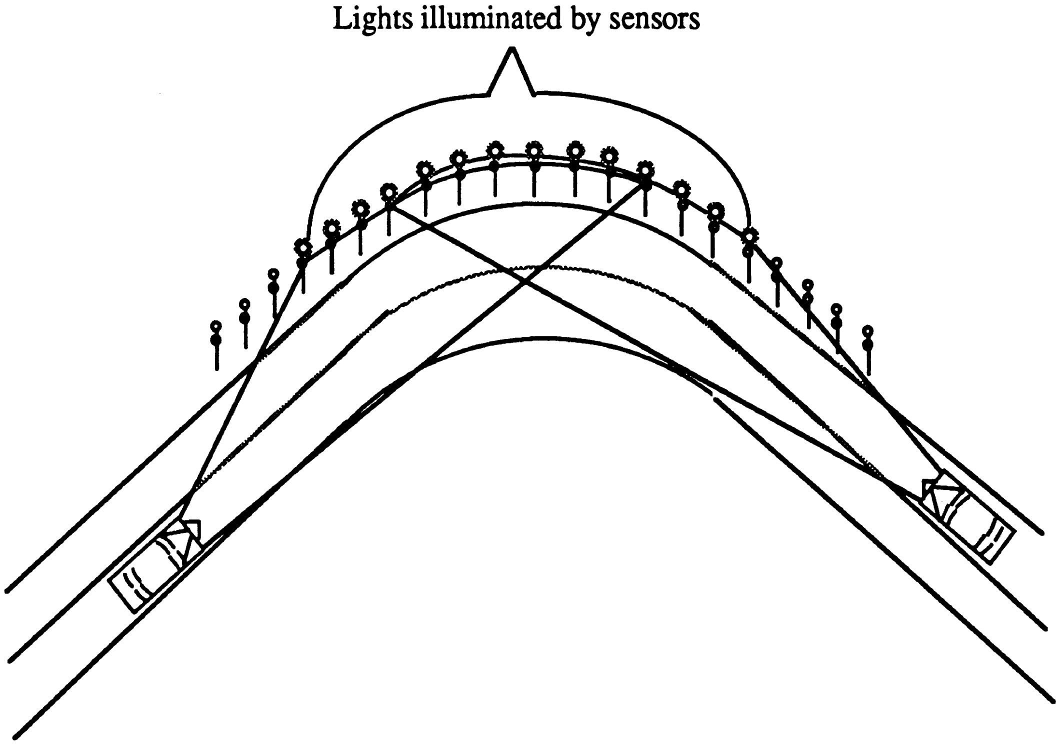


Figure 41. Schematic of a limited sight curve.

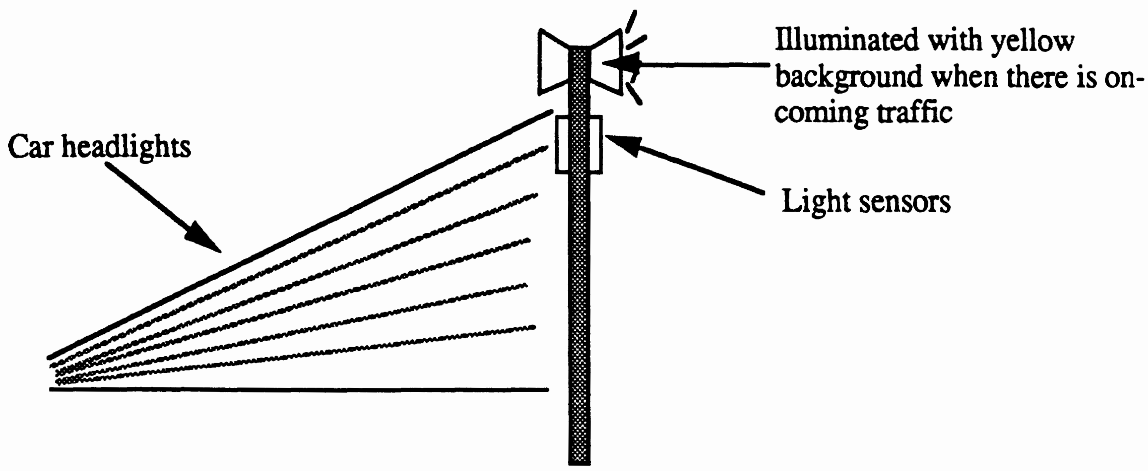


Figure 42. Warning posts on a limited sight curve.

Performance and functional specifications

The performance goal is to provide drivers with information of oncoming traffic before they reach stopping-sight distance (SSD). The aim is to provide drivers with an advanced warning so they will be prepared to react faster if an emergency arises. For this particular situation, the system should provide enough time for the driver to slow the vehicle and make the appropriate maneuver. (It should be noted that highways are built with enough sight distance to stop for an object in the road, but not for avoiding an oncoming vehicle.)

In this situation, the system is intended to provide a warning at a distance between oncoming vehicles that is the equivalent of the SSD between a vehicle and a fixed object. SSD on a given curve is, by definition the distance required to see far enough to stop for an object in the road. The closing rate of oncoming vehicles is $2V_d$ (where, V_d is the velocity). Hence, according to the intention of this countermeasure, the stopping sight distance for oncoming vehicles (SSDV) would be two times stopping-sight distance for objects, thus:

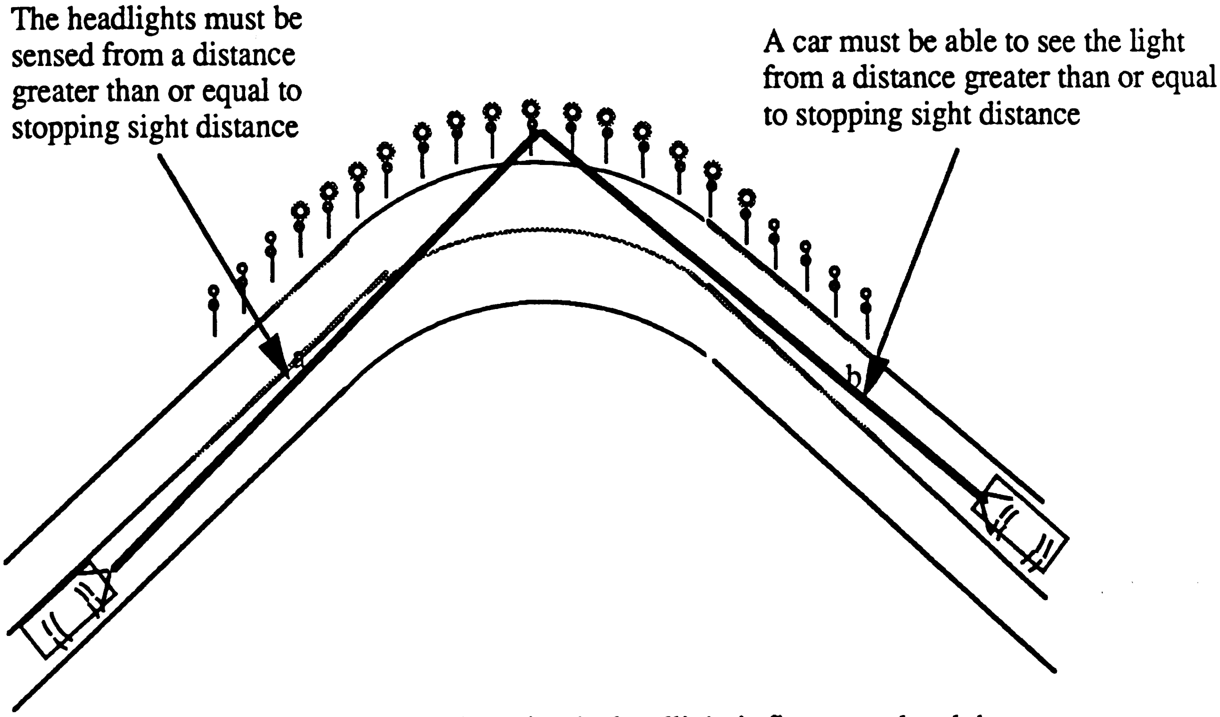
$$SSDV = 2SSD$$

The system would be designed so that when two oncoming vehicles are SSDV from each other, they are able to see each other or a light informing each vehicle of the presence of oncoming traffic. (See figure 43.) In summary, the range of the headlight sensor is equal to the

SSD for the curve and the range at which the warning light can be seen is also equal to the SSD for the curve.

Equipment needed

- Light sensors that can distinguish between headlights and other forms of light.
- Posts with lights in both directions on which the sensors are located.
- Controller and communication link from light sensor to lights.



The distance between the cars at the point the headlight is first sensed and the light is first seen is at least two times the stopping sight distance: a+b ≥SSDV.

Since the cars are driving towards each other, closing rate is two times the velocity. This gives the drivers the equivalent of stopping sight distance for an on-coming vehicle if they were both to come to a complete stop.

Figure 43. Stopping sight distance.

Warning of the presence of oncoming vehicles

General concept

This concept is applicable to roadways with limited sight distance because of a curve or hill. The envisioned system uses vehicle-presence detectors to recognize the presence of oncoming vehicles. This information indicates to drivers that vehicles are coming. Note that this is not an indication that it is safe to cross into the other lane if the signs are off, but added information of oncoming traffic. A schematic diagram portraying a hypothetical implementation is given in figure 44. This countermeasure is aimed at reducing the number of head-on collisions by providing drivers with enhanced awareness of the presence of oncoming vehicles.

Presentation to the driver

The display units are signs placed in the driver's line of sight. They have a picture of a car with a yellow background that lights up when there is an oncoming vehicle. A warning message of "Vehicle Coming" is given. (See figure 45.)

Sensing the situation

Vehicle-presence sensors (weight actuated, ultrasonic, magnetic, etc.) detect vehicles approaching and continuing through particular points of interest such as a horizontal curve or a crest vertical curve. Every sensor is paired with a warning sign. An example of possible location of these sensor-sign pairs is given in figure 44.

Performance and functional specifications

Time and intensity levels involved — The goal would be to provide the driver with information of oncoming traffic before they reach stopping sight distance. (See figure 46.) This would give the driver more time to react. When an approaching vehicle is sensed on the major roadway, the appropriate warning lights are activated for a set period of time T. For most cases, this period will be a function of the design speed of the highway and the distance of the sensors from the curve. If another vehicle passes the sensor before the time expires the period is reset.

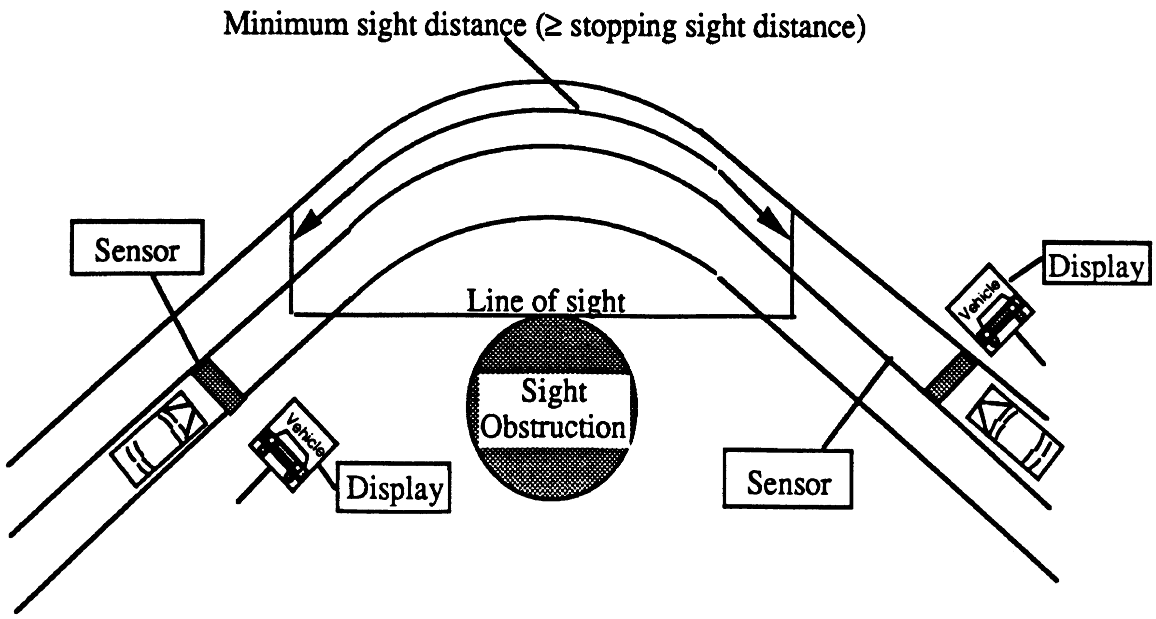


Figure 44. Schematic of a limited sight curve with a single sensor-sign pair.

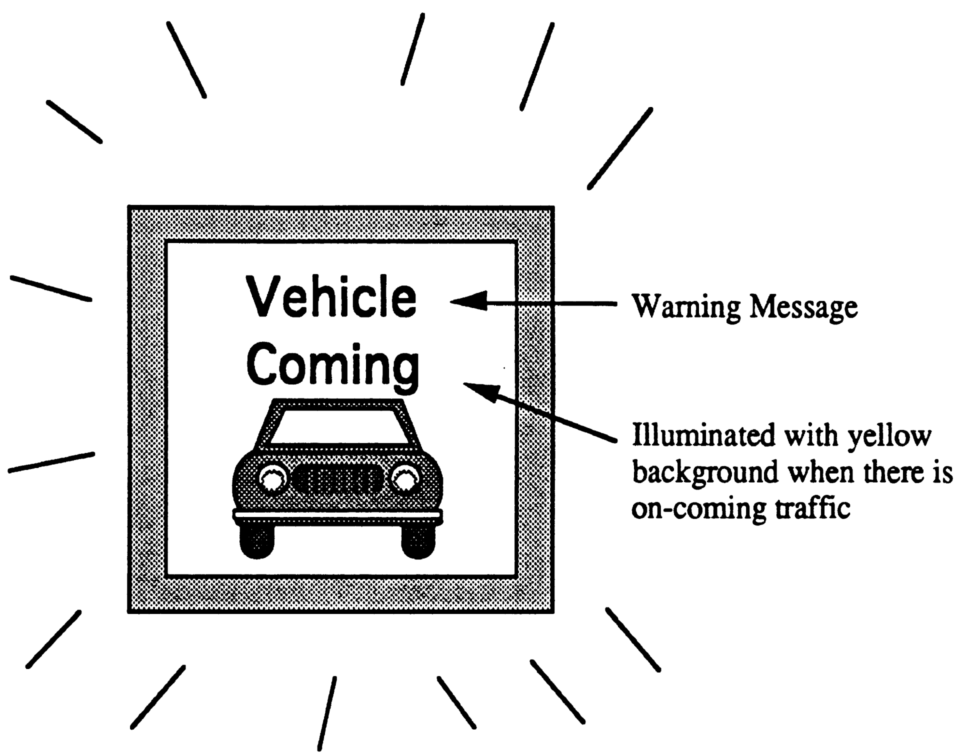
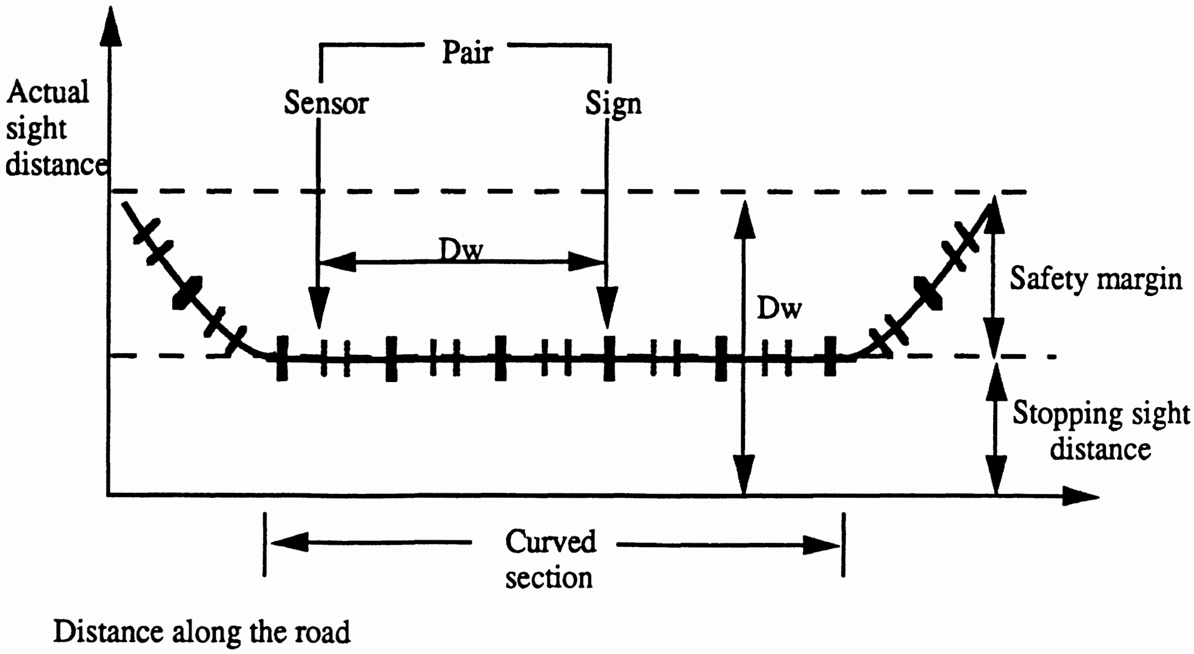


Figure 45. Warning sign on a limited sight curve.



1. Stopping sight distance = $2V_d + V_d^2 / 19.32$
2. Safety margin = $4V_d$
3. Dw is Stopping sight distance + Safety margin
4. Arrange signs along the road where the actual sight distance is less than Dw.
5. The distance between a sign and its corresponding sensor is Dw.
6. The distance between signs is determined for each case using the distance at which the sign can be read.

Figure 46. Sight distance along a curve.

Vehicle motion ideas – For this particular situation, the system should provide enough time for the driver to slow the vehicle and make the appropriate maneuver. It should be noted that highways are built with enough sight distance to stop for an object in the road, but not for avoiding an oncoming vehicle.

Kinematic and vehicle motion constraints – In this situation, the system will have to provide a warning at a distance (Dw, from the sensor to the sign) that is far enough that the driver can perceive and respond to the warning before reaching the stopping sight distance. Stopping sight distance is the minimum sight distance on a given curve, that by definition must be enough of a distance to stop for an object in the road. Driver's reaction time is 2.0 s. The closing rate of oncoming vehicles is $2V_d$ (V_d is the velocity), using a 2.0 s warning the distance at which the sign can be seen would be $4V_d$. Therefore, we want the warning distance, Dw, to be:

$$2V_d + \frac{V_d^2}{19.32} + 4V_d = Dw$$

Figure 46 shows a diagram of distance relationships. Note: These signs would be used when the minimum sight distance (the actual distance on the curve that the driver can see ahead) is less than Dw.

Equipment needed

- Sensors.
- Communication link from sensor to display-controller.
- Display-controller that keeps display light on from first sensor actuation until last vehicle reaches the display point.

Lane-keeping

General concept

This countermeasure system is intended to aid in keeping vehicles in their lane, thereby helping to prevent run-off-the-road and head-on crashes. The envisioned system would have a sensor in the car that detects when the car is going out of the lane boundaries defined by the road. If a car was veering out of its lane, automatic steering would be applied. The system would also alert the driver with an audible warning if the system could not make a sufficient correction. This system could be overridden by the driver.

Presentation to the driver

The driver is aware of the system only if the vehicle deviated from the path in the road without using a turn signal. When the car veers without signal, a small torque is applied to the steering to adjust the direction to align with the path. The torque needed for automatically steering the vehicle is expected to be small enough to be overridden by the driver if the driver chooses to do so. There could also be audible warnings if the vehicle departed appreciably from the stripe without having its turn signal on. The driver can turn the system off all together, the driver can turn the wheel with more force, or use turn signals to disable the lane following system so that the driver can change lanes.

Sensing of the driving situation

The purpose of the system is to keep the vehicle within the boundaries of its lane. The road includes a special stripe (having a magnetic or other detectable property) running down the center of the lane (see figure 47). There is a sensor installed in the vehicle to detect the vehicle's position with respect to this stripe (see figure 48). To provide preview for steering the vehicle, there may need to be auxiliary stripes or marks that indicate the direction and radius (curvature) of the road ahead. To adjust the vehicle's position, if necessary, a steering actuator is used. The control system is expected to steer the vehicle to follow the center stripe with enough fidelity to stay close to the center of its lane.

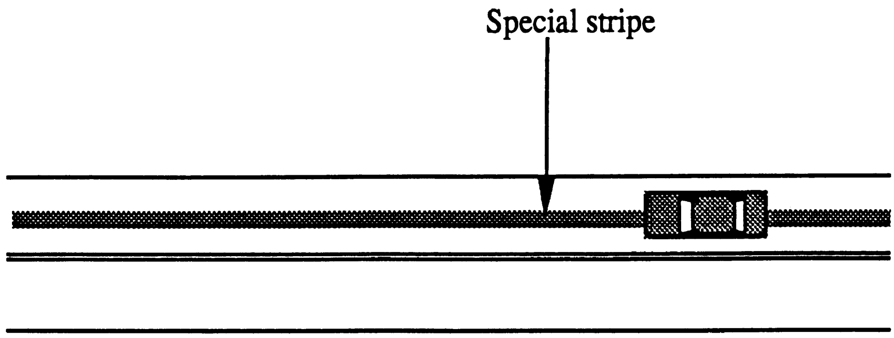


Figure 47. Location of stripe in the road.

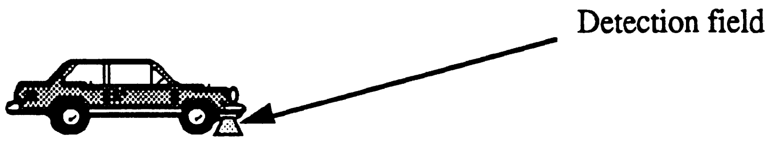


Figure 48. Location of lane sensor on the vehicle.

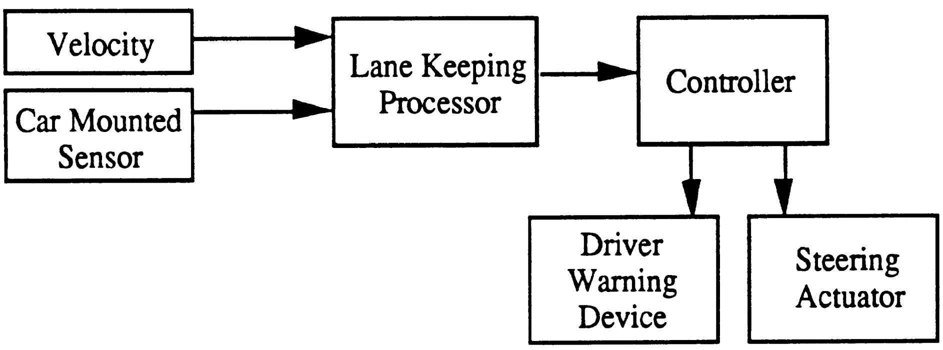


Figure 49. Lane-keeping flow chart.

Performance and functional specifications

The sensor, located on the underside of the vehicle, would relay to the on-board processor the location of the vehicle relative to the road. If the vehicle was within M (where M is a predetermined distance) of the lane edge, the correction system would be activated. An automatic swerving maneuver to reposition the vehicle would be applied to the steering system. The maneuver would change the lateral position of the vehicle back to the center of the lane. The on-board processor would also determine if the system could handle the correction or if the driver should be alerted. After a correction, if the vehicle was more than M away from the lane edge, the warnings would stop and the system would reset. Figure 49 shows a flow chart for the system.

In designing the system, certain constraints should be applied. The lateral acceleration should be no more than 4 ft/s^2. The yaw rate should not exceed 0.1 rad/s This corresponds to maneuvers that would be classified as normal driving. To effectively apply these constraints, the vehicle's steering gain would be a function of velocity. It is envisioned that the sensor and its associated processor would have a computation frequency of 20 Hz.

(Lane following is an old idea that is now being reconsidered. The Japanese talk about a "leaky" cable. The people at PATH have been considering magnetic nails at the lane edges. We had a visitor who invented a paint containing magnetic filings. Perhaps there is technology available today to create a virtual track.)

Equipment needed

- Detectable stripe in the road.
- Car-mounted sensor for detecting the stripe in the road.
- Processor for: (1) predicting location of the vehicle in relation to the lane and (2) generating warnings and steering commands.
- Warning device to alert driver that the system cannot sufficiently keep the vehicle in the lane.
- Steering actuator that can apply limited steering torques for swerving. (These torques might be limited to no more than 2 or 3 ft-lb, measured at the steering wheel.)

Warning drivers on a minor road of the presence of vehicles on a major road (stop signs)

General concept

This countermeasure addresses crossing-path accidents at intersections without signals and is applicable to intersections where the minor approaches are controlled by stop signs. This would be useful at isolated rural intersections, at locations where it is difficult to provide adequate sight distance, or during poor visibility conditions.

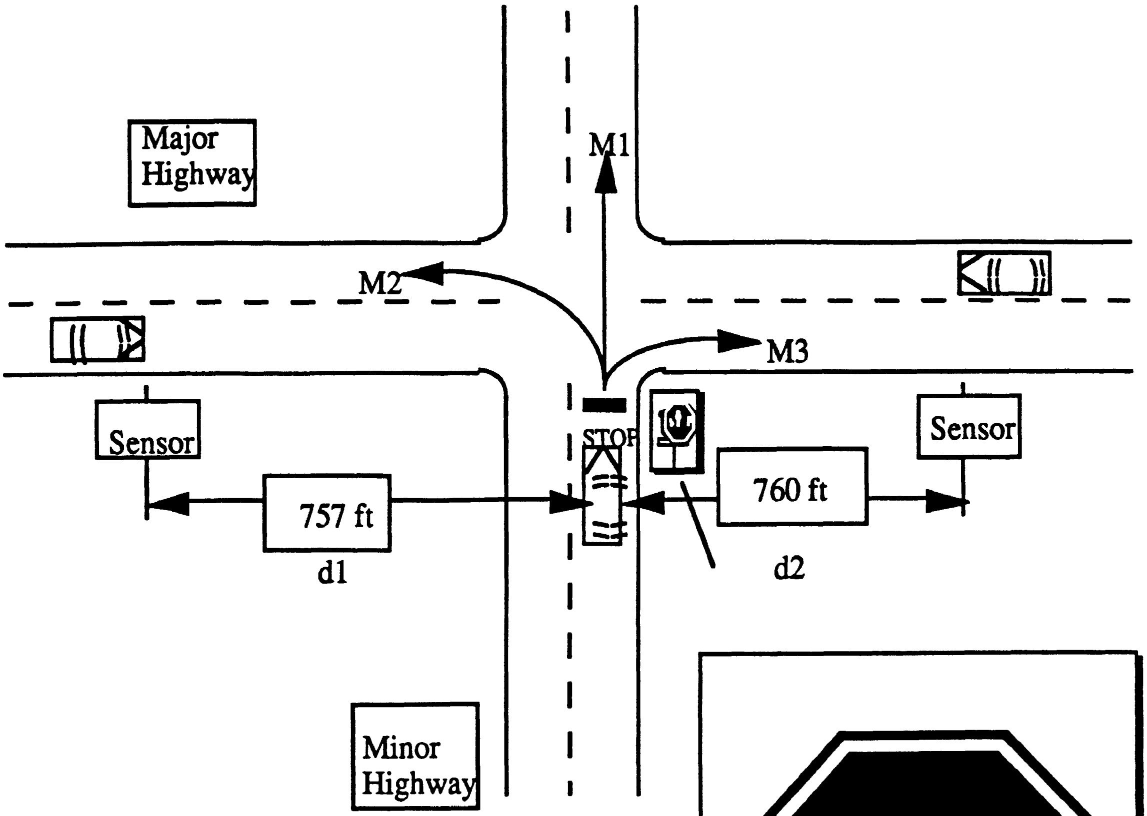
The stop signs on the minor approaches have an additional display that indicates the presence of vehicles on the main roadway approaching the intersection. The indicators show whether a vehicle is approaching from the left or from the right or from both sides. The intent is to let the driver at the minor intersection know that there is a vehicle approaching on the through road and that it is not safe to attempt a turning or crossing maneuver. Note that this is not an indication that it is safe to attempt the maneuver, just that a crossing or turning maneuver should not be attempted.

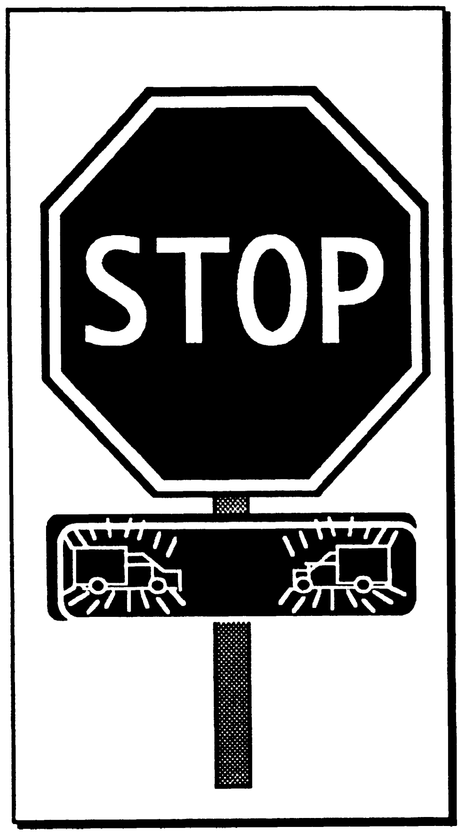
Presentation to the driver

Two flashing lights will be incorporated into the existing, standard stop sign. The lights will be placed on the right and left sides of the face of the sign to indicate from which direction the vehicle on the major roadway is approaching. Figure 50 is an example of how the stop sign might appear to the driver.

Sensing of the driving situation

At most major/minor intersections, there are three possible maneuvers for the vehicle on the minor road. These maneuvers are: (1) a crossing maneuver, where the vehicle simply crosses the major road without obstructing the traffic flow from the right or left on the major road, (2) a left turn where the vehicle must clear oncoming traffic approaching from the driver's left and safely merge with the traffic stream coming from the driver's right, and (3) a right turn where the vehicle must clear oncoming traffic approaching from the driver's left and safely enter the traffic stream. The time required to perform these maneuvers depends on vehicle factors, the geometry of the intersection, and the design speed of the major roadway.





AASHTO site distance values for a stopped passenger vehicle on a level, undivided, two-lane major highway with 12-ft lane widths. The design speed of the major highway is 55 mi/h.

M1 = Stopped Vehicle Crossing a Major Highway
d1 = 525 ft
d2 = 525 ft

M2 = Stopped Vehicle Turning Left onto Two-Lane Major Highway
d1 = 525 ft
d2 = 760 ft

M3 = Stopped Vehicle Turning Right onto Two-Lane Major Highway
d1 = 757 ft

1 ft = 0.305 m, 1 mi/h = 1.61 km/h

Figure 50. Warning drivers on a minor road of the presence of vehicles on a major road.

In order for the warning lights to properly indicate the approach of a vehicle, sensors must be located along the major roadway. The distance from the intersection to the sensor will also depend on the time required to perform the maneuvers. If the intersection was designed according to the policies developed by the American Association of State Highway and Transportation Officials (AASHTO), then minimum sight-distance guidelines were followed. These sight-distance values can be used as an initial estimate of where to place the sensors along the major roadway. The AASHTO guidelines define a sight-distance for each type of maneuver mentioned above. Because this countermeasure does not include indicators to sense which of the three maneuvers the vehicle is going to perform, sensor range and sight distance values should be conservative. For example, if the sight distances for crossing a particular intersection are less than those to perform a left-turn maneuver, the sight distances from the left-turn maneuver would be used to determine the range of the sensors. Figure 50 is an example for a passenger car and a level, undivided highway (12 ft lane width) with a design speed of 55 mi/h (80.7 ft/s). For this example the sensor for traffic approaching from the right would be placed approximately 760 ft from the stopped vehicle. Vehicles approaching from the left will be sensed at approximately 757 ft from the stopped vehicle.

Processing

When an approaching vehicle is sensed on the major roadway, the appropriate warning lights are activated for a set period of time T. For most cases this period will be a function of the design speed of the highway and the distance of the sensors from the intersection. For the above example, T = sensor distance / (.85 * design speed) = 11 s. If another vehicle passes the sensor before the time expires, the period is reset. (See figure 51.)

Equipment needed

- Sensor for vehicles to the right.
- Sensor for vehicles to the left.
- Communication from the sensors to sign-controller and from sign-controller to sign.
- Sign-controller/processor that determines when to illuminate vehicle icons (right and left channels are independent).
- Sign with vehicle icon.
- Optional: presence of vehicle on the minor road indicator.

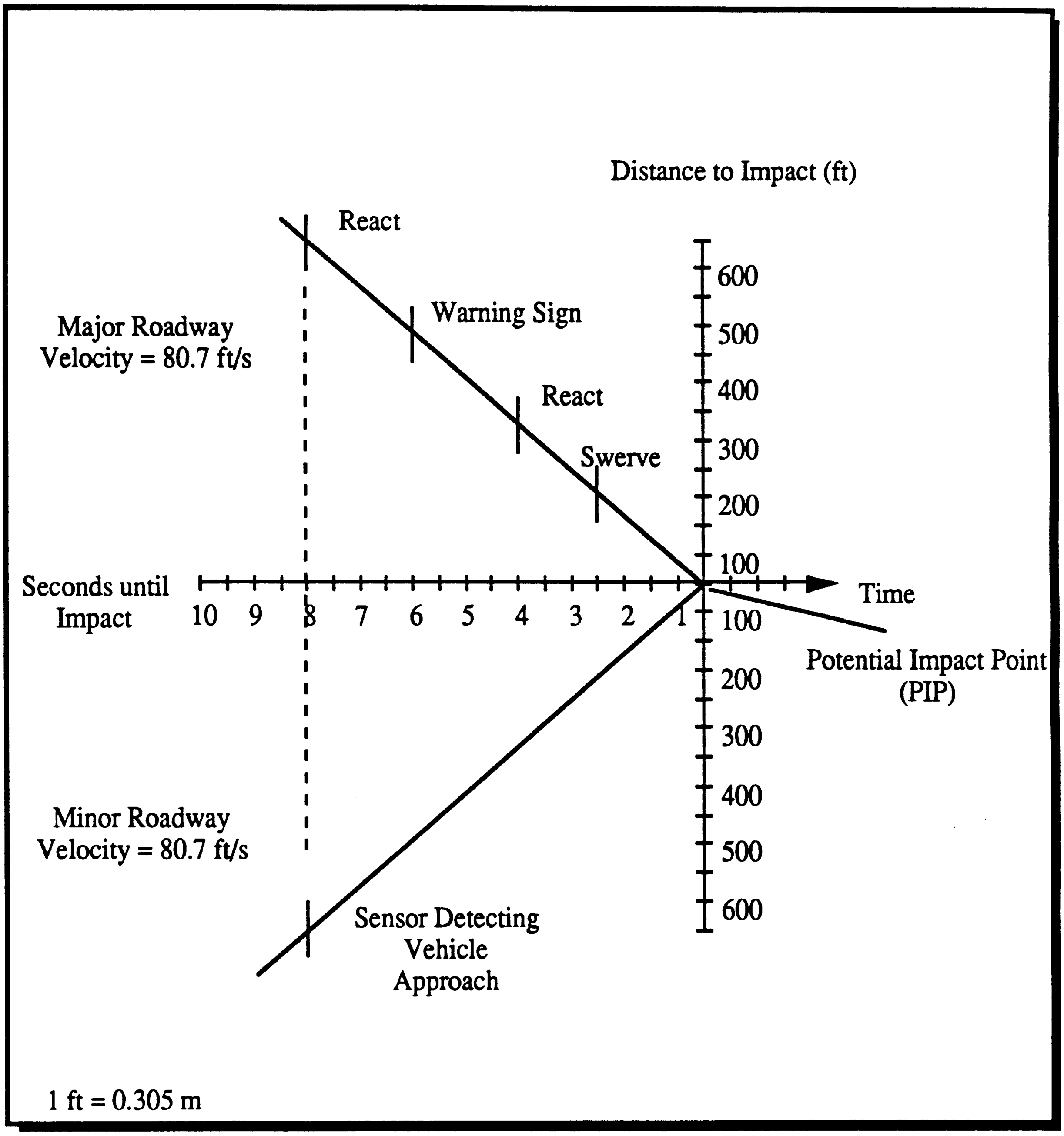
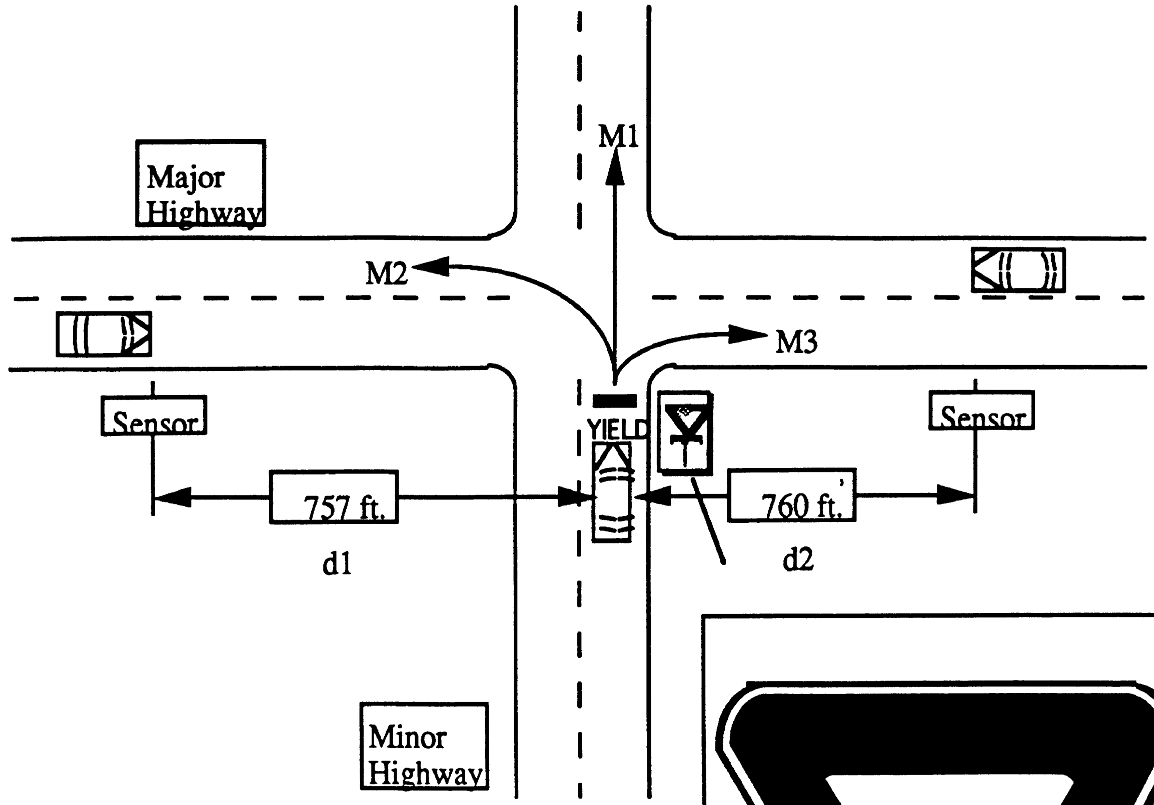


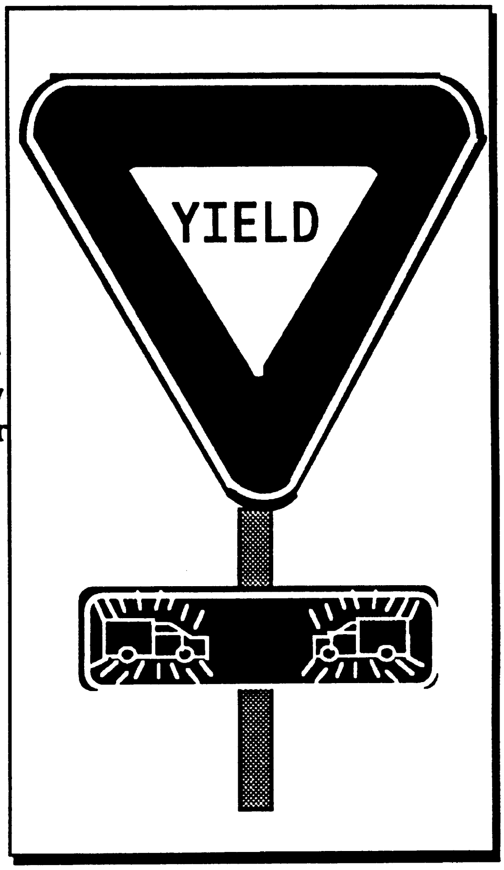
Figure 51. Major road warning design chart.

<u>Warning drivers on a minor road of the presence of vehicles on a major road (yield signs)</u>

General concept

This countermeasure addresses crossing-path accidents at intersections without signals and is applicable to intersections where the minor approaches are controlled by yield signs. This countermeasure is the same as the stop sign counter measure on the preceding pages, with a yield sign in place of a stop sign. Figure 52 represents the road layout and the sign design.





AASHTO site distance values for a stopped passenger vehicle on a level, undivided, two-lane major highway with 12-ft. lane widths. The design speed of the major highway is 55 mi/h.

M1 = Stopped Vehicle Crossing a Major Highway
d1 = 525 ft
d2 = 525 ft

M2 = Stopped Vehicle Turning Left into Two-Lane Major Highway
d1 = 525 ft
d2 = 760 ft

M3 = Stopped Vehicle Turning Right into Two-Lane Major Highway
d1 = 757 ft

1 ft = 0.305 m, 1 mi/h = 1.61 km/h

Figure 52. Warning drivers on a minor road of the presence of vehicles on a major road.

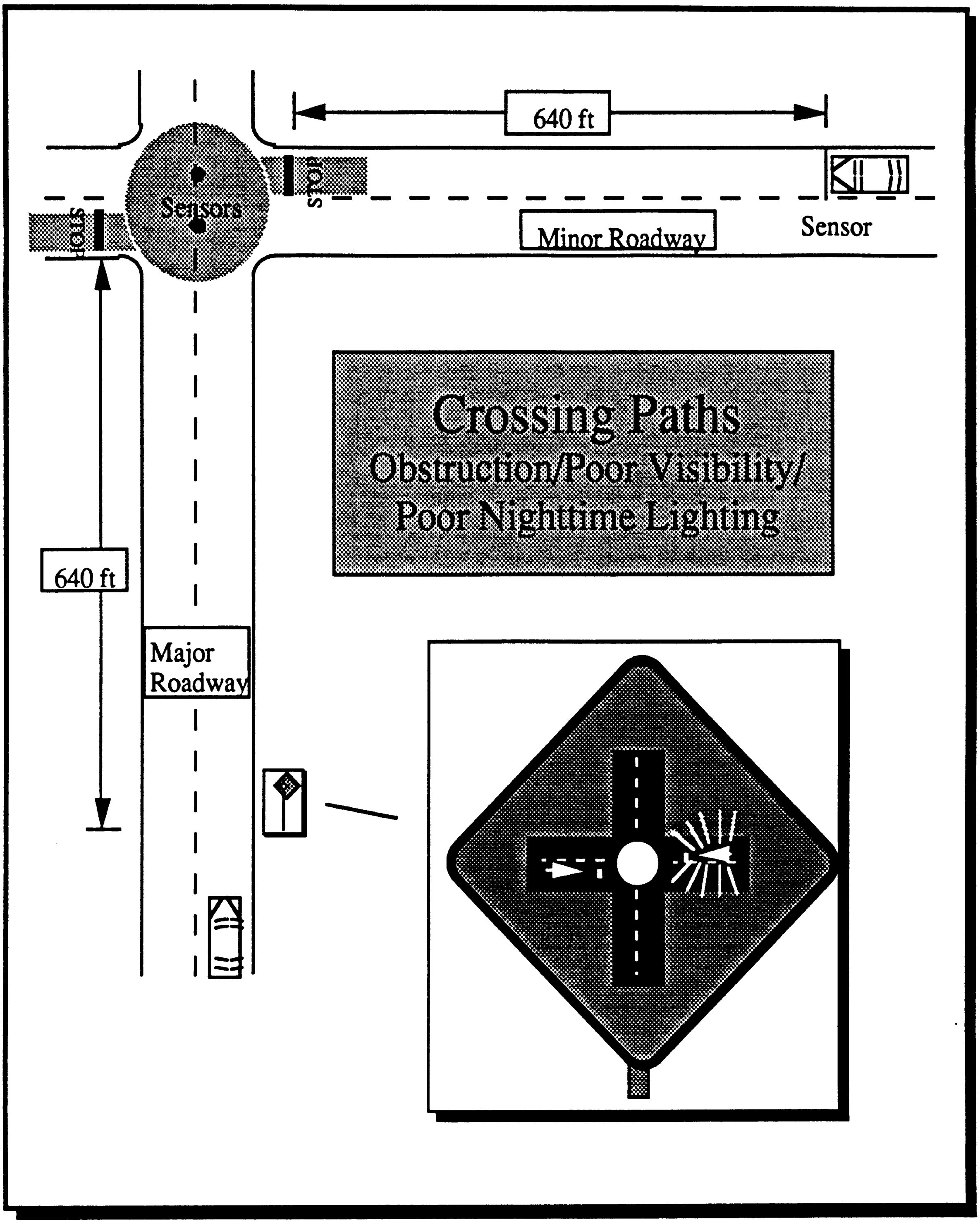
Warning drivers on a major road of the presence of vehicles on a minor road

General concept

The general concept is to employ active-safety technology to inform drivers on major roadways of the presence or approach of other vehicles on minor roadways at an upcoming intersection. This concept should be particularly helpful when inadequate vision (fog, rain, poor nighttime lighting) or limited sight distance are the main causes of accidents at these intersections. The countermeasure is envisioned to enhance the current method of posting warning signs indicating an "Intersection Ahead" or a "Blind Driveway." Its goal is to inform the driver on the major roadway of two potential hazardous situations. The first is a warning that vehicles are in or waiting at the intersection and braking or maneuvering may be necessary. In this situation, vehicles may be turning left from the major roadway onto the minor roadway or they may be entering or crossing the major roadway from the minor roadway. The second is a warning that vehicles are approaching the intersection on the minor roadway. This informs the driver that there is a possibility that both vehicles may cross the intersection at the same time providing the vehicle on the minor roadway fails to yield. This countermeasure addresses crossing-path accidents and left-turn accidents at intersections without signals. Figure 53 shows a schematic of the potential countermeasure for a four-way intersection.

Presentation to the driver

The present "Intersection Ahead" warning sign shows a schematic of the intersection ahead. The new countermeasure enhances this idea by incorporating flashing lights to alert the drivers of a potential conflict. Depending on the type of intersection (three- or four-way), these new signs will have two or three flashing lights. At a four-way intersection, where the minor roadway crosses the major roadway and continues, the sign has three lights. Two are positioned on each minor leg of the schematic and are activated when vehicles on the minor road approach the intersection. Depending on the direction of approach, the corresponding light on a minor leg begins flashing. The third light is located in the center of the schematic and is activated when vehicles are waiting at or in the intersection. These vehicles may be entering the major roadway from the minor roadway or they may be turning left from the major road onto the minor road. At three-way intersections, only two lights are needed, one on the minor leg and one in the center of the schematic.



1 ft = 0.305 m

Figure 53. Warning drivers on a major road of the presence of vehicles on a minor road.

Sensing of the situation

The sensors for this countermeasure will have two functions. The first is to sense the presence of vehicles waiting at the intersection. These sensors could be similar to those currently used at signalized intersections to detect the presence of vehicles. The second sensor will be located a distance away from the intersection on the minor roadway and is envisioned to be a simple switching device. As a vehicle passes this sensor it simply turns on the corresponding warning light. All sensors will have to transmit simple on/off information to the warning signs along the major roadway.

Processing

When an approaching vehicle is sensed on the minor roadway, the appropriate warning lights are activated for a set period of time. If another vehicle passes the sensor before the time expires, the period is simply reset. The sensor to indicate the presence of vehicles waiting at the intersection turns the warning lights on only when vehicles are sensed within its sensing range, with no time delay after the vehicles have left the intersection.

Performance and functional specifications

Time and intensity levels involved – Today the advanced warning signs informing the driver of an intersection ahead are placed at a distance that allows the driver a reasonable perception, recognition, understanding, and response time (PIEV time). The distance at which the signs are placed is site specific, although in average situations (i.e., no grades, no sight distance problems), a PIEV time of about 3 to 5 s is adequate for a driver on the major approach. It is envisioned that the flashing signs will have a frequency of approximately 0.5 s and will be bright enough to be easily distinguished during daylight hours as well as during heavy fog and rain.

The location of the warning signs on the major roadway will primarily depend upon the design speed of both the major and minor roadways. Of course, sign locations will also depend on the topology of the land and sight distance obstructions. Assuming a typical intersection, the following example outlines the steps needed for positioning the warning signs and sensors on the major and minor roadways, respectively. Given that both roads are located in a rural setting with design speeds of 55 mi/h (80.7 ft/s) it is possible to work backwards in time from the potential impact point (PIP). Figures 54 and table 2 illustrate that a driver on the major roadway needs 2.5 s to swerve (swerving requires the least amount of time of any of the accident avoidance maneuvers) to avoid a collision. This assumes a lateral acceleration of 8.05 ft/s^2 and results in a lateral displacement of 8 ft. If a 1.5 s reaction time is added (typical for the average driver), then the driver will need at least 4.0 s and 323 ft to avoid a collision by swerving. Let's assume, however, that stopping is also to be included as a means of avoiding a collision. Table 1 illustrates that it will require just over 5.0 s for the vehicle to stop using a deceleration rate of 0.25 g. Using the same reaction time as above, the driver will need at least 6.5 s to either stop or swerve to avoid a collision. This corresponds to placing the signs 525 ft (80.7 ft/s • 6.5 s) from the intersection. The next issue to rationalize is where should the vehicle on the minor roadway trigger the flashing lights and how long should they stay on after being activated. In the worst case, the vehicle on the minor roadway reaches the intersection at the same time as the vehicle on the major roadway, or 6.5 s. Therefore, the triggering mechanism will need to be placed at least 525 ft from the intersection along the minor roadway. Once activated, it can also be reasoned that the flashing lights should stay on at least 6.5 s. However, only in a very few (but potentially deadly) situations is the vehicle on the minor roadway not going to slow down Therefore, the duration that the lights are activated needs to be greater than 6.5 s. If the vehicle is going to come to a complete stop at the intersection, we can use the following equation to calculate the deceleration needed:

$$D = \frac{V^2}{2A}$$

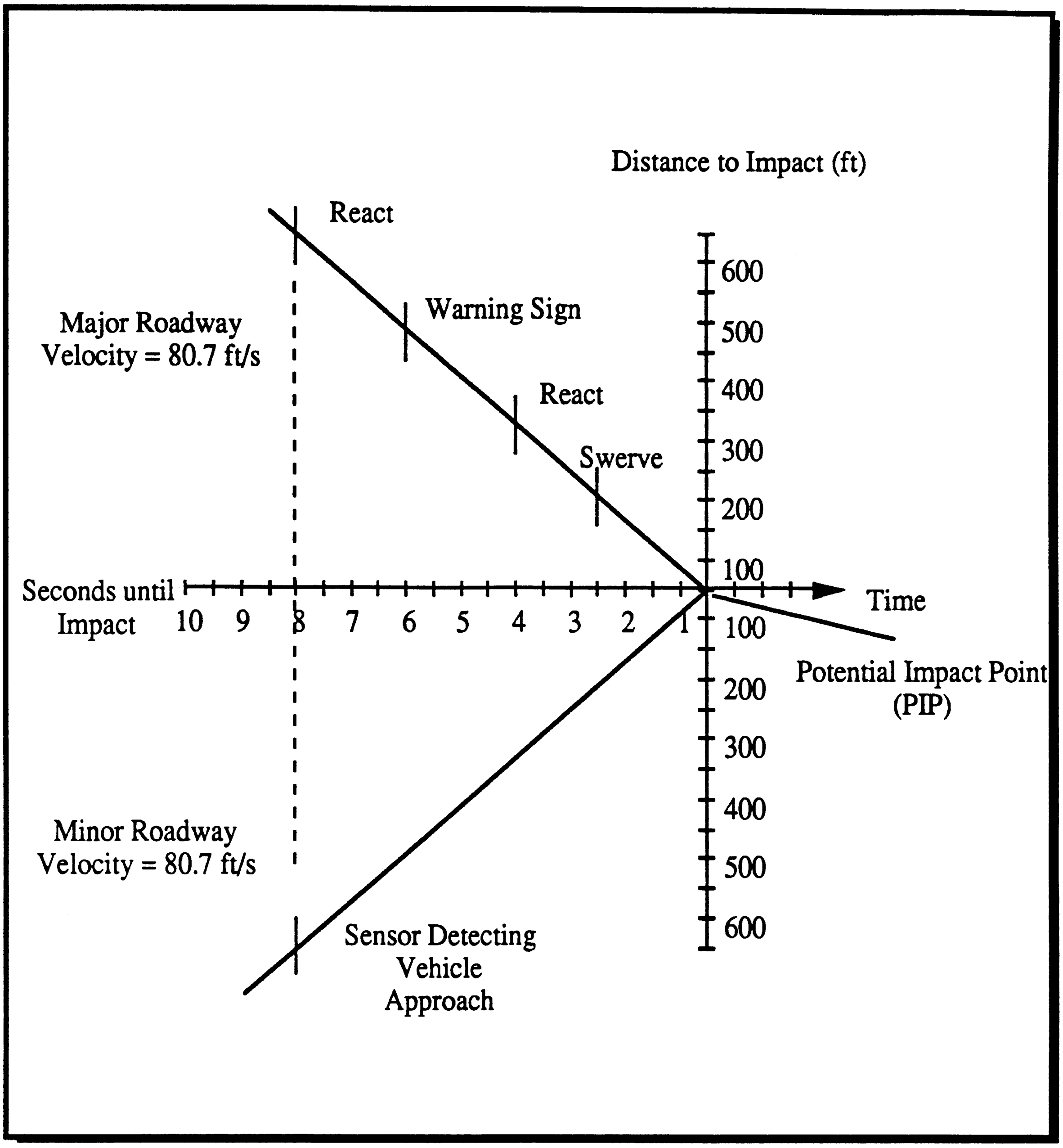
where: D = distance = 525 ft

V = velocity = 55 mi/h = 80.7 ft/s

A = deceleration

The resulting deceleration rate is 6.2 ft/s^2 The time needed to reach the intersection is found by dividing the velocity by the deceleration:

$$T = \frac{V}{A} = 13 \text{ s}$$



1 ft = 0.305 m

Figure 54. Major road warning design chart.

Thus, if the flashing lights are activated and remain on for 13 s, they will for this particular scenario indicate that there is a vehicle approaching or waiting at the intersection.

The second set of sensors is located at the intersection to detect the presence of vehicles waiting to cross or turn on to the major roadway. These sensors will behave similarly to those used to sense vehicles waiting at a signalized intersection. When there is a vehicle either waiting at the intersection or waiting to turn left from the major roadway onto the minor roadway, these sensors will indicate this by relaying a signal to the flashing lights located in the center of the intersection schematic. This will warn the driver on the major roadway that there is traffic at the upcoming intersection and that caution, reduced speed, and alertness are necessary to avoid any potential traffic conflicts.

Kinematic and vehicle motion constraints – Assumes both vehicles can decelerate at a minimum of 0.25 to avoid the possibility of a collision at the intersection.

Driver constraint – Ability to recognize and understand a flashing sign at least 1.5 s [120 ft @ 55 mi/h (37m @ 89 km/h)] before passing it.

Functional Requirements Goals for the Sensors and Processing Unit

Processing time – Should be very short - microseconds

Environmental penetration – If possible, rain, snow, darkness, ice, etc.

Equipment needed

- Sensor for presence of vehicle away from the intersection on the minor road (two required for each approach to the intersection).
- Sensor for a vehicle in the intersection or at the stop signs.
- Communication links between sensors and sign-controller(s) and lights on the signs.
- Sign-controller(s) for lights on signs. (This controls the length of time the lights are on. At the intersection, the light is on as long as there is a vehicle at or in the intersection. Approaching-on-minor-road lights are on for 13 s after sensing the latest vehicle pass.)

Cooperative intersection–four-way stop right-of-way indicator

General concept

This concept is applicable to three- and four-way stop intersections where right-of-way is controlled by stop signs and arrival sequence of the vehicles. This type of countermeasure would prevent accidents and increase the uniformity of traffic flow through intersections. It would also aid drivers during inclement weather situations or when insufficient lighting causes poor visibility. The concept is to provide an additional indicator built into each stop sign that informs the driver that the intersection is clear and it is safe to enter and perform a maneuver through the intersection. To accomplish this, two types of sensors will be required. One will detect if a vehicle is occupying the area at the stop line of a particular approach. The second will monitor the presence of vehicles within the intersection. A microprocessor will use the sensor information to determine the sequence of arrivals at the stop lines and determine the appropriate order and time for vehicles to enter the intersection. This countermeasure addresses crossing accidents at intersections controlled by three- or four-way stop signs.

Presentation to the driver

Each stop sign at an intersection has a yellow indicator light mounted on top of the sign as shown in figure 55. The indicator light is off when a vehicle is not present in its corresponding lane or if another vehicle is performing a maneuver within the intersection. When the intersection is clear, the appropriate indicator light is activated to signal the respective waiting vehicle that it is safe to enter and perform a maneuver within the intersection. As soon as that vehicle enters the intersection the light turns off again. The indicator lights are also visible to the drivers of vehicles at the other approaches, informing them which vehicle has the right-of-way.

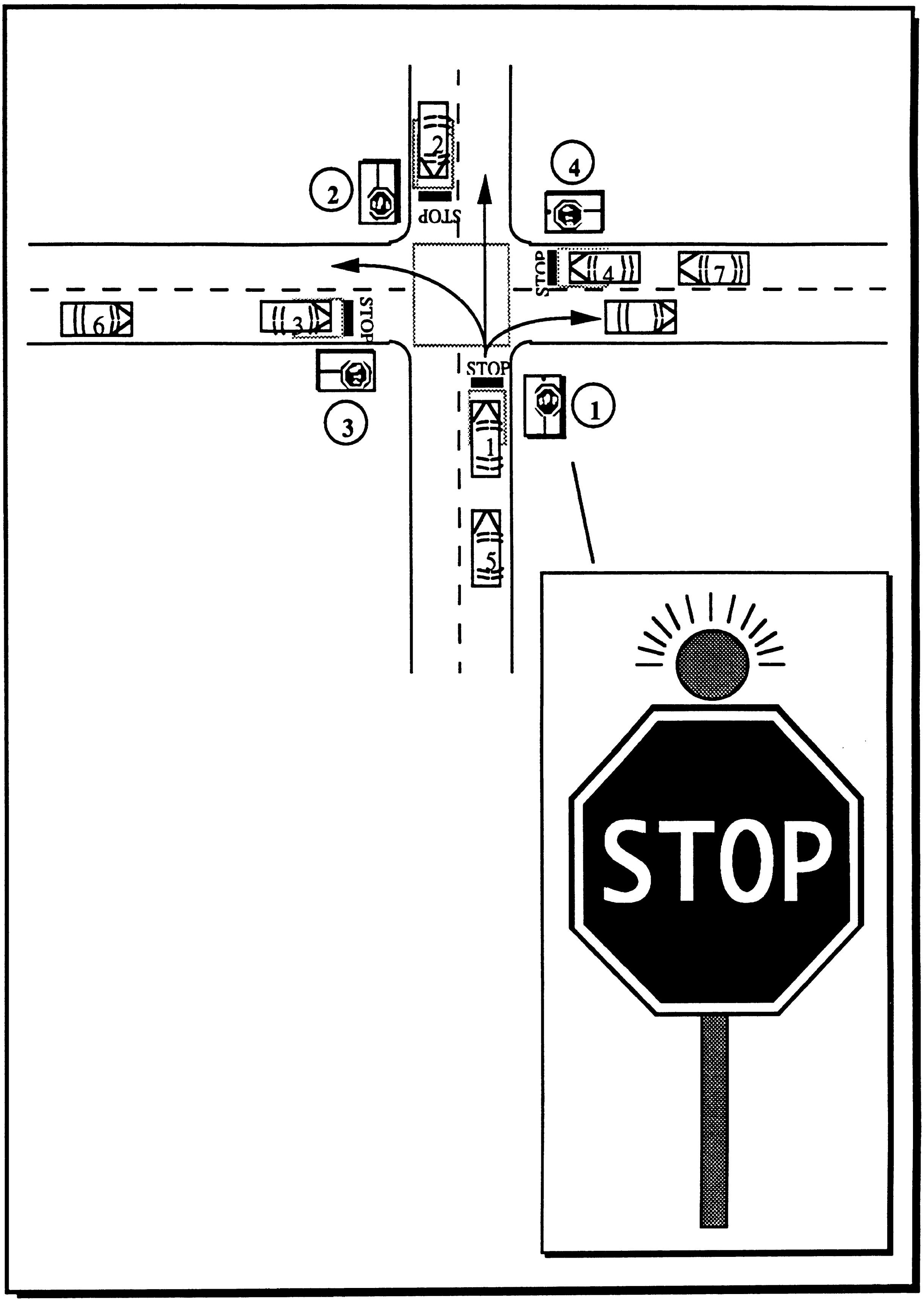


Figure 55. Cooperative intersection - four-way stop right-of-way indicator.

Sensing of the driving situation

Each stop sign has a sensor to detect a vehicle's presence and time of arrival at its corresponding stop line. A different sensor also monitors the presence of a vehicle within the intersection. All sensor information is constantly fed to a microprocessor that determines the sequence of arrivals of vehicles at their respective stop lines. With this information, the microprocessor determines which vehicle is next in the queue and signals that driver by activating the yellow light, showing that the intersection is clear and it is safe to proceed. When the second sensor detects that the vehicle is in the intersection, the microprocessor turns the yellow light off. Figure 56 is an example timing diagram for the four-way stop pictured in figure 55.

Equipment needed

- Vehicle presence detector for each approach located at the stop sign.
- Vehicle presence detector for a vehicle in the intersection.
- Processor for determining who has the right of way (also takes care of timing even if people go out of order).
- Wiring (communication) to processor and lights.
- Right-of-way lights on stop signs.

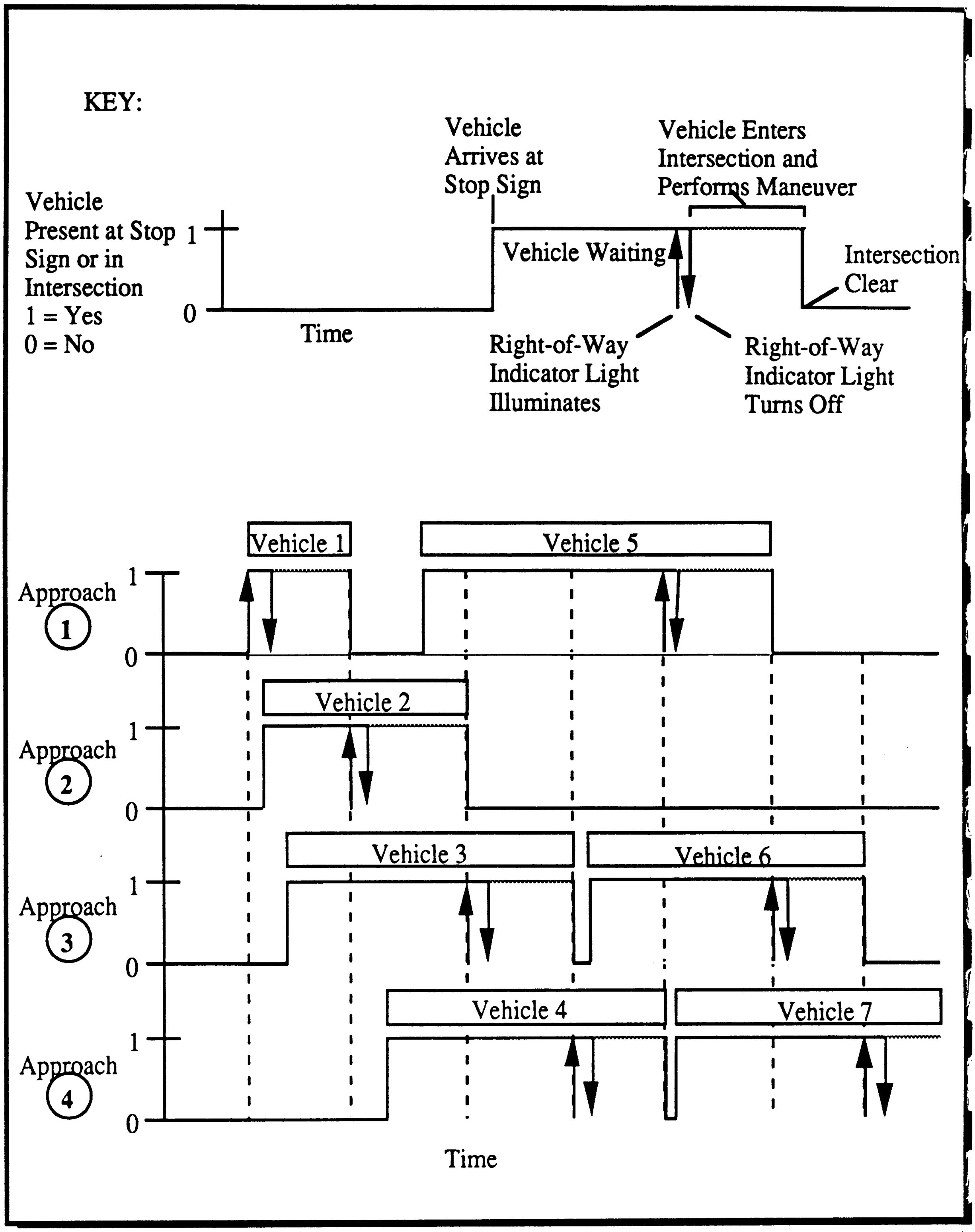


Figure 56. Timing diagram for a four-way stop.

Approaching vehicle warning for driver making a left-hand turn and warning of vehicle turning left ahead

General concept

This concept is applicable to intersections where a driver wishes to turn left from a major road onto a minor road or isolated driveway. This countermeasure would be particularly useful along four-lane major roads where a vehicle turning left poses a combination of driving hazards. The countermeasure is based on two different warning signs. The first, placed at the intersection, would warn the driver of the turning vehicle if an approaching vehicle is within a dangerous distance. This would help the driver judge if there is sufficient time and distance to attempt crossing the oncoming traffic lanes. The second sign (only applicable where there is no center left-turn lane), placed before the intersection, would warn drivers approaching from the rear of the turning vehicle that it is turning left and braking or that a lane change maneuver may be necessary. Figure 57 is a schematic of the proposed countermeasure. This countermeasure addresses rear-end and left-turn accidents at intersections without signals.

Presentation to the driver

For the driver turning left, a sign with the words "Left Turn" and two flashing red lights will be located where it can be easily seen by the driver before the turn is attempted. Figure 57 has the sign placed at the intersection of the two roads, adjacent to the right lane of the minor road. When the lights are flashing, they indicate that an oncoming vehicle is approaching the intersection, and a left turn should not be attempted. The second warning sign is located along the major road and it has a schematic of the potential traffic situation. It has two flashing yellow lights. When a vehicle slows and signals to turn left, a sensor activates the flashing lights on the sign. This will inform vehicles of the traffic situation ahead so that they can begin braking or maneuvering into the right lane to avoid having to stop behind the turning vehicle. Figure 57 shows how this sign might appear.

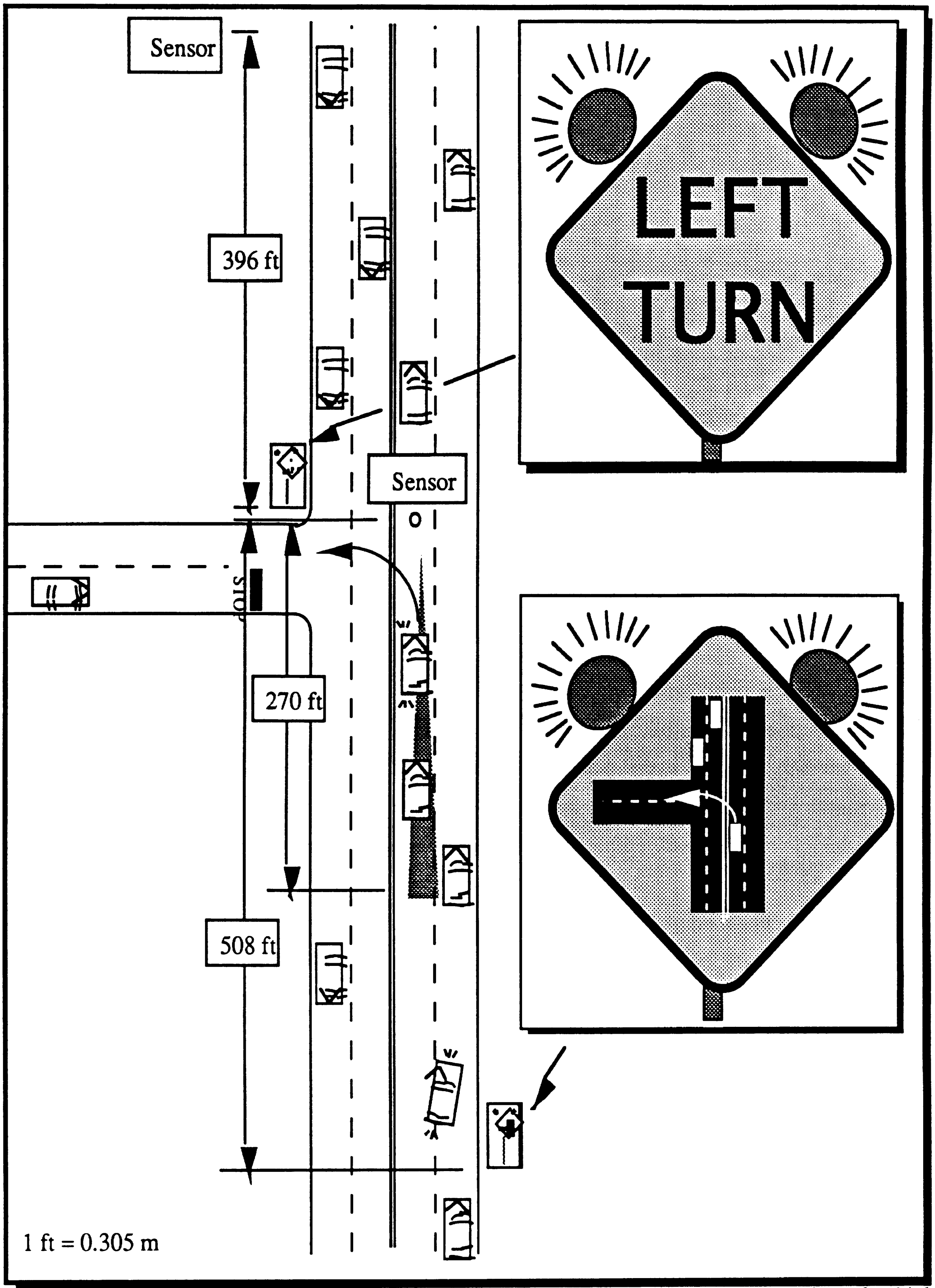


Figure 57. Approaching vehicle warning for driver making a left-hand turn and warning of vehicle turning left ahead.

Sensing of the driving situation

Two different sensors are necessary for this countermeasure. The first is located along the major roadway where it senses a passing vehicle (heading toward the intersection) and activates the red flashing lights on the left-turn sign for a fixed period of time. If another vehicle passes the sensor before the time expires, the period is simply reset. The time period and distance from the intersection to this sensor are dependent on the time it takes for the turning vehicle to complete its maneuver and the design speed of the road. The second sensor will be located at the intersection and must be able to determine when a vehicle is going to turn left. To do this there are two possible options: (1) It could detect when a vehicle's left-turn signal is on, or (2) it could measure the deceleration of the vehicle, and based on some previously defined deceleration rules, determine if the driver intends to turn left. Because this sensor is going to control the sign that informs vehicles of the traffic situation ahead it must be able to sense that a vehicle is turning left as soon as possible. The distance from the intersection to the vehicle turn-warning sign is a function of how far in advance the sensor can detect a vehicle turning left.

As an example, suppose the design speed of the major road depicted in figure 57 is 45 mi/h (66 ft/s). If the intersection was designed according to the policies developed by the American Association of State Highway and Transportation Officials (AASHTO), then minimum sight-distance guidelines were followed. These sight-distance values can be used as an initial estimate of where to place the sensors along the major roadway. The AASHTO guidelines define a sight distance necessary for turning left across oncoming traffic lanes. Using these guidelines, a conservative estimate of the time it takes to perform the left turn under the given circumstances is 6.0 s. This time assumes the driver comes to a complete stop, analyzes the traffic scene, and does not have to wait for oncoming traffic. This would put the sensor for the left-turn sign approximately 396 ft (6.0 s • 66 ft/s) from the intersection. Once activated, the left-turn sign should stay on for at least 6.0 s. The second sensor, which detects the vehicle turning left, should have a range of approximately 270 ft. This is the distance it takes a vehicle to come to a complete stop if traveling at 45 mi/h and decelerating at 0.25 g. The time it takes for the vehicle to stop is 8.2 s. Allowing the sensor 2.0 s to determine if a particular vehicle is going to turn left, leaves 6.2 s for the vehicle to reach a stop at the intersection. By adding a reaction time of 1.5 s to the 6.2 s, the maximum total time to warn vehicles about the upcoming traffic scene is determined. At the design speed this corresponds to placing the sign approximately 508 ft (7.7 s • 66 ft/s) from the sensor.

Equipment needed

1. Approaching vehicle warning for a driver making a left-hand turn:
   - Sensor for observing occurrence of a passing vehicle.
   - Communication of passing observation to the sign-controller.
   - A sign-controller for illuminating the left-turn warning when there is not a sufficient gap to make a left turn (light stays on for 6 s after the last vehicle passes it even if there was a preceding vehicle that turned the light on).
   - Sensor for observing presence of a left-turning vehicle.
   - Sign with lights (display).

2. Warning that a vehicle ahead is turning left:
   - A display for drivers behind the vehicle turning left.
   - Communication of the presence of a left-turning vehicle to the display (the presence sensor would be the one used in part A).

CHAPTER 5. RELATIONSHIPS AMONG COUNTERMEASURE SYSTEMS, FUNCTIONAL REQUIREMENTS, AND TECHNOLOGY

INTRODUCTION AND SUMMARY

Active-safety countermeasure systems (CMS) consist of a combination of sensing, processing, communications, and display technologies. Of these, sensing technology is considered to be the limiting technology both in terms of cost and procurable implementation. The sensing aspect of Active Safety Technology (AST) will be emphasized throughout this chapter.

This section will present the approach and rationale for the structure of this chapter, as well as an overview of the tasks and requirements of this work. This effort examined a broad class of technologies for implementing countermeasure functions (CM) that would be either infrastructure based or vehicle based in their deployment. Infrastructure-based countermeasures typically require vehicle or pedestrian presence detection at one or more locations. Vehicle-based implementations, on the other hand, tend to be oriented toward range and velocity monitoring technologies and vision enhancement for the driver (i.e., blind spot coverage, night vision, weather penetration).

In addition to the infrastructure-based versus vehicle-based distinction, this report categorizes sensors into point-versus-imaging and passive-versus-active genre. Imaging sensing is performed by delineating between different spatial regions of a scene. Point sensing is taken to be any nonimaging sensing mode including presence at a single point and presence within an area.

In general, multiple technologies are applicable and available for implementing a given CM, and therefore a technology trade-off analysis should be conducted considering cost, feasibility, deployment, reliability, availability, etc. before selecting specific technologies. Some CM that would otherwise be impossible for any of the proposed technologies (by the current state-of-the-art) are made possible through the use of cooperative vehicles and infrastructure.

The next section provides an assessment of the technologies available for implementing each countermeasure function. As discussed above, the emphasis has been placed on the evaluation of sensing technologies. It is important to discuss, up front, the phenomenology and science of each sensing technology in order to understand the required implementations and applications for each of the countermeasure functions. Although a specific technology is used for implementing a generic function, such as an infrared sensor for measuring thermal contrast, its implementation will be countermeasure specific. Furthermore, sensing technologies, such as microwave, infrared or visible, can be divided into vehicle-based and infrastructure-based countermeasures, and further subdivided into imaging and point detection functions. Additionally, sensing systems can be either active or passive in nature. It is believed that a general treatment of available technologies is best presented first, categorized by their "location," whether or not they are imaging, and active or passive. At which point their application to each countermeasure function, if applicable, can be discussed in a more meaningful manner. The second section will contain an illustrative table to depict the structure of the technology treatment, as well as a large number of references giving examples of applicable research and marketed products.

The section entitled, "Functional/performance requirements" treats each countermeasure function individually from a sensing perspective and treats all countermeasure functions collectively from a processing, communications, and display viewpoint. Having laid the technology groundwork in the previous section, this section is prepared to correlate these technologies with countermeasure functions via functional requirements. Matrices are provided to facilitate understanding. Extensive discussions are provided, depicting the complicated interrelationships between technologies, particularly sensing and countermeasure functions.

SENSING-TECHNOLOGY ASSESSMENT

Sensors for the 19 proposed countermeasure functions require the following measurement capabilities: presence detection, entrance/exit detection, range monitoring, velocity measurement, velocity monitoring, vision enhancement, driver condition monitoring, and weather monitoring. To further detail the scope of sensing, many of these functional requirements can be implemented by several distinct technologies. For example, velocity can be ascertained via multiple-point presence detectors separated in space (or equivalently in time), providing a short-term average velocity, or alternatively velocity may be directly measured via the Doppler signature of a moving target, providing instantaneous velocity measurement. The choice of a specific approach, assuming multiple technologies exist, is application specific and generally depends on cost and minimum performance requirements. No single technology is a panacea for all of the functional requirements that the countermeasure functions precipitate. In this section, each technology will be presented and discussed as a member of a sensing class defined by the columns in table 21. For example, the first class of sensors discussed will be vehicle-based, point presence, and passive. That is, all sensors that are vehicle-mounted and passively sense a small region in space called a point. All sensor technologies in a given sensor class will be discussed in one subsection. A comparison subsection is provided for each section containing more than one pertinent technology.

Table 21. Sensor classification.

Sensing Modality	Vehicle				Infrastructure			
	Point		Image		Point		Image	
	Passive	Active	Passive	Active	Passive	Active	Passive	Active
Microwave		√			√	√		
Millimeter Wave		√			√	√		
Infrared		√	√		√	√	√	√
Visible		√	√		√	√	√	
Acoustic		√				√		
Magnetic						√		
Piezoelectric					√			

In addition to the technologies presented in table 21, there exist additional technologies, such as seismic-sensing, pneumatic tubes, and pollution-sensing, which will not be further expounded upon due to lack of permanence, maturity, or practicality. Two countermeasure-specific technologies, namely, driver condition monitoring devices and weather monitoring sensors, will also be treated in the next section outside of the tabular structure.

Vehicle-based, point detection, passive (V-P-P)

According to table 21, there are no sensor technologies that are applicable to vehicle-based, point, passive detection (V-P-P). The reason is not a lack of capable technologies, but rather a lack of applications. Vehicle-based sensing requirements are generally related to either the acquisition of range or velocity information, or vision enhancement. The desire for instantaneous measurement of range or velocity provides a strong bias towards an active system. As will be seen later, average velocity can be determined by the infrastructure using passive, point detection. In the case of night vision enhancement, one is typically interested in an imaging sensor. Conceivable V-P-P technologies would be weather sensors or sensors for monitoring driver condition. Both of these will be discussed separately in a later section.

Vehicle-based, point detection, active (V-P-A)

For the triplet, vehicle-based, point detection, active (V-P-A) sensor, table 21 indicates multiple applicable sensing technologies. Systems based on radar principles (i.e., transmission and reception of a wave form to determine range or velocity) can be designed and built to operate in many different sensor modes ranging from microwave and millimeter wave, to infrared and visible. Also, sonar systems utilizing acoustic waves are all relevant to the V-P-A triplet. These technologies provide the range and velocity monitoring capabilities needed for longitudinal control, lateral positioning, and related functional requirements.

Microwave and millimeter wave (MMW)

Microwave radar and millimeter wave (MMW) radar operate in the wavelength region spanning from 100 cm to 3 mm. This corresponds to a frequency range between 0.3 GHz, GHz (P band) and 100 GHz (W band) within the electromagnetic spectrum. Microwave and MMW radar directly measure instantaneous relative range. Velocity also can be measured instantaneously by exploiting the Doppler shift of the returned signal. The signal reflected from a target will either be red-shifted (lower frequency, indicating an increase in relative velocity), or blue-shifted (higher frequency, indicating closure between the equipped vehicle and the target). The frequency shift imposed on the transmitted wave form is linearly proportional to the relative velocity. Alternatively, velocity may be calculated by differencing sequential range measurements, separated by known time intervals (e.g., the pulse repetition frequency or modulation period).

Radiation can be transmitted in a rapid succession of narrow pulses or in a continuous wave form (CW), modulated either in amplitude or frequency. Operating in a pulsed mode, a radar system determines the range from the target to the sensor by timing the round-trip travel time of the pulse. The location of the target in range can be measured more accurately by utilizing very short pulses, however, short pulses generally have high peak-power requirements. Alternatively, pulses of long time duration provide superior Doppler or velocity resolution. In other words, a longer duration temporal signal provides higher resolution in the spectral domain. CW modulation allows fine range resolution while keeping peak-power requirements low and average power high. Range is determined based on the phase delay of the received signal relative to the phase of the transmitted signal, which can be measured by any one of a number of phase detection schemes.

Microwave and MMW radar systems are well suited for the V-P-A triplet. Examples are applications requiring active ranging, velocity monitoring, longitudinal or headway control, obstacle detection, collision warning and avoidance, adaptive cruise control, lateral control, and lane following. In addition, blind-spot detection, both side and rear, can be implemented utilizing microwave or MMW sensors. Typically, a microwave beam can be tailored or shaped, through proper antenna design, to cover the required region (i.e., a lane of traffic) without incurring false returns from objects outside the desired region of interest (i.e., vehicles in other lanes or overpasses). Antenna sizes or form factors of less than 1 ft in diameter generally provide sufficient resolution for vehicle-based applications that typically include ranges of a few hundred feet.

Microwave and MMW radars are relatively insensitive to adverse weather conditions, particularly over the short ranges typically involved in automotive applications. In addition, they are robust with respect to diurnal variations, providing consistent performance around the clock. The reason being that as active systems they provide their own illumination source and therefore are not vulnerable to signature variations due to ambient or diurnal changes. These same variations fundamentally limit the performance of passive sensors. The operational envelope of microwave and MMW radar is therefore continuous.

For nearly 20 years, companies have been developing vehicle-based radar systems. Bendix developed a 36-GHz, frequency-diplexed, braking system in 1974. In the same year, Toyota and Nissan were experimenting with short range, 10-GHz radar for air bag deployment. In 1977, RCA developed a 22.5-GHz, linear frequency-modulated continuous wave (FMCW), braking/mitigation radar, while Sel-Dalmier-Benz was developing a 35- GHz, FMCW, warning radar, and Nissan Mitsubishi was developing a 24-GHz, pulse/Doppler radar. Since that time, several other companies have been involved in the development of automotive radar. The evolution of automotive radar is summarized chronologically in table 22.

During a recent PROMETHEUS-DRIVE session of the International Conference on Automotive Electronics, Phillips and GEC Plessey both independently decided to use FMCW chirp wave forms for headway control applications. Both teams have reportedly developed vehicle-mounted radar systems, demonstrating effectiveness for adaptive cruise control. To date, neither team has integrated the sensor with automotive engine or braking functions. In addition, the Plessey team has developed a prototype MMW obstacle detection radar. The projected price of these MMW radar units is under 100 British pounds in production quantities.

Table 22. Microwave/MMW radar for VPA.

Company	Frequency	Modulation	Type	Period
Nissan	24-GHz	Pulse-20 ns	Warning	1970
Auto-Stop	10.5/24-GHz	Diplex/Pulse-20 ns	Braking	1973
Bendix	36-GHz	Diplex	Braking	1974
Sperry	1.75-GHz	Pulse-2 ns	Warning	1974
Toyota	10-GHz	FMCW	Air bag	1974
Nissan	10-GHz	FMCW	Air bag	1974
Bendix	22-GHz	AM/FM	Braking	1977
RCA	9/18-GHz	FMCW	Warning	1977
RCA	22.5-GHz	FMCW	Braking	1977
Ford			Braking	1977
Sel-Dalmier-Benz	35-GHz	FMCW	Warning	1977
Nissan Mitsubishi	24-GHz	Pulse/Doppler	Braking	1977
RCS	33.4-GHz	Diplex	Braking	1977
GM	8-12-GHz	Pulse-1 ns	Warning/Braking	1978
Lucas	32.6GHz	FMCW	Braking	1978
AEG TST	35,80,94-GHz	FMCW/Pulse-20 ns	Braking	1979
VDO	35-GHz	Pulse/Doppler	Warning	1980
Rashid	24.5-GHz	FMCW		1981
Toyota Fujitsu	50-GHz	FMCW	Warning/Braking	1981
Philips	94-GHz	FMCW	Braking	1981
Nissan	10GHz	Pulse/Doppler (Binaural)	Warning	1983
Rashid	10-GHz	FMCW	Braking	1984
Nissan Meisei	60-GHz	Pulse/Doppler		1985
RCS/Vorad	24.5-GHz	Diplex	Warning	1987
SSDD AR-2	35-GHz	FMCW	Warning	
Munich T Univ	94-GHz (Imaging)	Pulse-1 ns	Warning	1988
Rashid	24.5-GHz	Diplex		1988
CAS	24-GHz	Pulsed	Braking	
Bosch	35-GHz	Pulse/Doppler	Warning	Current

Vorad, formerly RCS of San Diego, CA, currently manufactures a radar system for collision avoidance, and obstacle detection applications. This system has currently been installed in approximately 300 Greyhound buses, and is scheduled to be installed in Greyhound's entire fleet of 2400 buses. (See references 20, 26, 28, 36, 37, 44, 45, 47, 52, 54, 55, 59, 60, 61, 64, 68.)

Infrared and visible (laser radar)

Visible sensors operate in that portion of the electromagnetic spectrum from deep blue (approximately 0.3 micrometers, denoted µm) to red (0.7 µm). Infrared systems operate in the wavelength region spanning from where the red visible ends to approximately 30 µm. Infrared sources and detectors are based on several different technologies and materials, and typically operate over subbands or spectral windows within the infrared spectrum.

Laser radar is an active-sensing technology using optical radiation (visible or infrared) to illuminate a region or object of interest. The reflected signal is detected and processed to ascertain reflectance, range, and/or velocity information regarding the region subtended by the laser beam. Either pulsed or modulated CW operation provides the mechanism for determining range and velocity.

A single element, laser, range finder (e.g., point detector) can be used to monitor position or velocity relative to a lead vehicle or object for headway-keeping and obstacle-detection applications. Also, it has application to lateral control and road-following countermeasure functions, although it generally requires the implementation of a cooperative infrastructure (i.e., retroreflective tape on lane delimiters).

Laser radars are capable of extremely good spatial resolution due to the short wavelengths and small aperture sizes involved. Spatial resolution varies proportionally with the wavelength of the radiation source and inversely with the aperture diameter. The wavelength of optical radiation is short enough to permit use of small apertures while providing sufficient resolution for automotive applications.

Vehicular laser radars are currently in the research and development phase. The Japanese appear to be the biggest proponent of this technology, having published several research articles on laser radar systems for automobiles. These systems, however, are not presently in volume production. Also in Japan, Koito Manufacturing Limited has developed a laser diode, pulsed, collision- warning radar. Although current laser radar technology has not been implemented in large scale automotive applications, future developments are likely to make implementation of this technology viable. Preliminary research [at Nissan] has indicated that false alarms are currently a problem preventing vehicle-based installations for obstacle detection or longitudinal control countermeasures. Extensive data on reliability in the context of automotive environment do not exist. (See references 18, 42, 50, 57, 69, 72.)

Acoustic

Like electromagnetic radiation, discussed above, ultrasonic or acoustic waves can be used for detection and ranging applications. Acoustic sensors, as active systems, provide their own source of illumination. However, ultrasonic energy does not travel at the speed of light (670 million mi/h), but rather propagates at the speed of sound (760 mi/h). This means that in the time that the signal has traversed the path from the source to the target and returned, the target has likely moved significantly in range, thus restricting the applicability to scenarios with limited motion, particularly for the platform. Ultrasonic or acoustic sensors can, however, be calibrated (i.e., range-gated) to trigger a detection for any object within the preset range gate. Such sensors are, therefore, well suited for vehicle-based blind-spot monitors and for instances involving low velocity maneuvers (e.g., backing up).

Ultrasonic sensors are both economically feasible and readily procurable. Vehicle-based sensors to monitor vehicle blind spots or aid in backing up can cost as little as $150. Ultrasonic sensing systems are often vulnerable to acoustic interference effects and high-wind conditions. Unlike electromagnetic radiation, acoustic waves interact with wind, and thus performance will degrade in high-wind environments.

Many American companies market ultrasonic V-P-A sensors. Several examples follow. Technodyne Research of Lyndhurst, New Jersey, markets the Protex™ safety sensors line of backup ultrasonic sensors. Safety Technology, Inc. of Sparks, Nevada markets rear-motion-detection systems. Scan, a Dynatech Company, of Westford, Massachusetts offers both side- and rear-sensing capability. Trend Tec of Traverse City, Michigan offers a side mirror with an ultrasonic sensor and an LCD display that indicates the range to the nearest object in back of a large truck. EBI Inc. offers the Hindsight 20/20, an ultrasonic proximity sensor with a dash-mounted alarm that intensifies and changes pitch at very close range.

Comparison

Microwave and MMW radar systems demonstrate excellent weather-penetration capabilities in virtually all conceivable conditions, particularly over the short ranges involved in automotive applications. Laser radars may suffer significant degradation in performance when required to operate under adverse weather conditions. However, the short operation ranges typically permit operation in all but the worst of conditions. Weather-penetration capability in microwave and

MMW radar is superior to that of optical radar systems, although it is gained at a price of larger antennae (radar analog to optical aperture) for comparable resolution. The small antenna size requirement favors MMW radar over microwave radar, while weather penetration capability favors microwave radar between the two. Performance of acoustic wave systems also degrades with poor weather conditions, and is particularly susceptible to high wind conditions.

For operating frequencies residing within the spectral response of the human eye (i.e., in the visible and near-infrared region of the electromagnetic spectrum), care must be taken to choose power levels consistent with laser eye-safety considerations.

Active systems do not require any external source for illumination (e.g., sun) and generally operate equally well day or night. Any of the radar systems are well suited for range and velocity monitoring in high- or low-speed operations. Sonar systems are well suited only for V-P-A applications requiring low velocities.

From a cost and availability standpoint, currently only sonar systems are viable. However, the future holds great promise for vehicle-based radar systems.

Vehicle-based, imaging, passive (V-I-P)

For the triplet, vehicle-based, imaging, passive sensor, table 21 indicates two applicable sensing technologies. While imaging systems based on microwave and MMW radiometry are conceivable, it is unlikely that they will become viable because they are relatively complex and thus expensive. Infrared and visible imaging systems, while viable, are not currently in widespread deployment. These technologies are envisioned to provide nighttime vision enhancement capabilities.

Infrared

Passive infrared sensors, like their active counterparts, operate over selective bands within the infrared region of the electromagnetic spectrum. While active systems operate in very narrow bandwidths due to the monochromicity of the source (laser, microwave, or MMW), passive systems operate over wider spectral bandwidths, generally spanning several micrometers.

Infrared detectors are sensitive to emitted radiation in the thermal region of the electromagnetic spectrum. Passive infrared sensors must respond to the inherent thermal signature of a radiating object. Visible signatures are due mainly to reflected electromagnetic energy from an external visible radiation source and are therefore generally exploitable only during periods of external visible illumination. Thermal signatures are present regardless of external illumination and are strictly a function of object temperature and emissivity (a number between zero and one indicating the relative effectiveness of an object to radiate as a blackbody or perfect radiator). The thermal signature comes from radiative emission from any object at a temperature above absolute zero (-273°C). Peak infrared radiation at ambient terrestrial temperatures occurs in the long wave infrared (LWIR, 8- to 12-μm) region of the electromagnetic spectrum. Objects at higher temperatures (e.g., vehicle exhaust systems) will have peak radiation at shorter wavelengths.

In passive infrared systems, exploitation capability requires a minimal target to background thermal contrast. Under the majority of operating conditions, sufficient contrast is available and exploitable for detection purposes, however, contrast reversals typically occur twice a day, thus leaving insufficient contrast during transition times. One hundred percent temporal coverage presents a stringent requirement for passive sensors, as passive signatures vary strongly with illumination, reflectance, shadowing, and ambient conditions.

Imaging infrared devices are capable of generating spatially resolved pictures of thermal emission from a scene, and thus provide an aid to the driver as a vehicle-based night vision enhancement system. Animals, pedestrians, vehicles, and objects in the road can readily be detected by infrared detectors during nighttime driving.

For infrared V-I-P applications (e.g., night vision enhancement), the required level of thermal sensitivity necessitates that the infrared detectors must be cooled, either cryogenically or thermoelectrically Cryogenic cooling (requiring the use of liquid coolants typically liquid nitrogen or cryogenic refrigerators based on the Sterling cycle) are not a suitable solution to automotive applications from a cost standpoint. Thermoelectric coolers offer the only implementally feasible solution to V-I-P applications, but are currently cost prohibitive. Pyroelectric sensors require no cooling and can be procured in arrays or in scanning systems. However, performance measures such as the noise-equivalent-power, NEP (the signal level required for a signal-to-noise ratio of unity), or the specific detectivity D^* (area- and frequency-normalized inverse of NEP), are orders of magnitude (2 or more) worse than cooled detectors. In high thermal-contrast scenes, pyroelectrics may provide sufficient sensitivity, however, the cost of imaging systems is still prohibitive.

While imaging infrared systems for widespread vehicle-based installations are currently cost prohibitive, GM is developing a system to be released in 1994, at an estimated cost of roughly $1,000 dollars. The Japanese have incorporated Mitsubishi infrared, focal-plane arrays in their high-speed trains for night vision enhancement, demonstrating the feasibility and desirability of night vision technology.

Visible

Like passive infrared, passive visible signatures can be exploited for vehicle-based night vision enhancement applications. Low light-level television (LLLTV) is a potential technology for vehicle-based night vision enhancement, however, to date it has not been used as such. Rather than shifting to a portion of the electromagnetic spectrum where a stronger nocturnal signal exists (i.e., infrared sensors), LLLTV operates in the visible band with extremely sensitive detectors and image intensifiers. Even though nocturnal conditions may involve very low-level visible signatures, LLLTV is capable of detecting even a few visible photons and amplifying them, using image intensifiers to a level sufficient to make a clear picture of a nocturnal scene in the visible band.

The sensitivity of silicon-based charge coupled device (CCD) cameras is excellent and does not require any cooling mechanism. The technology is very mature, and as a result, cameras can be found with a very small form factor. Also, spatial resolution is very fine, being proportional to the wavelength of visible radiation and aperture size.

While the LLLTV camera may not be prohibitively expensive, the associated image intensifiers and electronics will likely preclude wide-scale deployment in the near term. Recall that its infrared counterpart has prohibitive cost problems as well, and also requires cooling of the detectors.

Comparison

The infrared region of the electromagnetic spectrum demonstrates improved weather penetration relative to the visible regime. However, for the short ranges involved in automotive applications, visibility is generally sufficient, except in extremely inclement weather where penetration will likely suffer in both regimes.

Both infrared and visible imaging sensors are easily capable of achieving the spatial resolutions required for night vision enhancement, however, current costs are prohibitive. In addition, thermally sensitive infrared imaging systems require additional cooling.

Vehicle-based, imaging, active (V-I-A)

For the triplet, vehicle-based, imaging, active sensor, table 21 indicates that there are no applicable sensing technologies. Active microwave or MMW radar imaging systems such as real aperture radar (RAR) or synthetic aperture radar (SAR) are too expensive and sophisticated for vehicle-based implementation. Either optical SAR or a three-dimensional imaging laser radar are conceivable, but not procurable from an economic perspective. If these technologies could become viable, active ranging and velocity monitoring could be greatly enhanced, giving spatial resolution in addition to range, or range and Doppler, simultaneously. Such a system would also be applicable to night vision enhancement. Providing its own source of illumination makes 100-percent temporal coverage possible.

Infrastructure-based, point detection, passive (I-P-P)

In general, infrastructure-based applications of sensor technology are going to be directed more toward presence detection rather than range and velocity monitoring. For the triplet, infrastructure-based, point detection, passive sensor, table 21 indicates five applicable sensing technologies. Most of these technologies are in widespread deployment or are easily achievable from a technology standpoint.

Microwave and millimeter wave

Passive microwave radiometers measure what is called the brightness temperature of a region of a scene subtended by the microwave antenna pattern. The brightness temperature depends strongly on the scattering albedo and emissivity of a region. The presence of a vehicle presumably will cause a detectable change in the measurable brightness temperature. For whatever reason (e.g., unreliable signal, difficult to exploit, expensive) there has been no literature uncovered reporting on microwave radiometry for these applications. For the weather sensors, microwave radiometers will show utility for measuring water depth upon the road surface.

Infrared

Single-element detectors have applicability to presence detection, particularly when a large thermal contrast exists between target and background. Pyroelectric sensors offer a means of detecting thermal contrast without requiring cooling of the detector elements. Pyroelectric detector systems can integrate over long periods of time, relative to scanning imaging systems, and also do not have readout noise associated with focal plane array imaging systems. Therefore, in general, sufficient signal levels to perform vehicle detection are available with single detector systems without incorporating any cooling processes.

Weather penetration in inclement conditions is likely to be poor. There are no electronic crosstalk or interference problems with locating multiple units in close proximity.

Passive infrared vehicle detectors are available on the market. For example, Microsense Inc. markets a passive-infrared, road-based vehicle detector called MIX The unit can be installed in either a head-on or side-fire configuration and is capable of detecting vehicles at ranges of up to 300 ft.

Visible

Visible photodiodes have application for detecting headlights of oncoming vehicles. This has direct application to scenarios involving vehicles coming over a hill or around a corner. The photodiode detectors can be filtered at the input to favor head lamp radiation and thus will not generate false alarms from other forms of stray radiation (e.g., reflected sunlight). Upon detection of oncoming head lamps a variable message sign or warning beacon may be activated.

Piezoelectric

Piezoelectric polymer technology converts a mechanical strain field to an electrical voltage. A mechanical force, applied to a piezoelectric material (e.g., a vehicle passes over it) induces a voltage proportional to the magnitude of the force (e.g., the weight of the vehicle) at the output. Each vehicle axle will induce a distinct and separate perturbation in the voltage versus time history that can be monitored by a control system. The mechanical piezoelectric polymer is a polarized strip sensor (up to 300 ft long) that is placed transversely across a road surface, either embedded in or in direct contact with the surface. Piezoelectric material also demonstrates pyroelectric characteristics, providing thermal detection capabilities. This report only considers implementation of piezoelectric properties (e.g., mechanical sensing capability) because the thermal capabilities are believed to be inadequate for vehicular and traffic applications.

Piezoelectric polymer sensors can be used to measure vehicle point presence, velocity, acceleration, weight, and direction of travel. A single piezoelectric strip can measure point presence and vehicle weight, while multiple sensors can be deployed to measure the additional parameters. Having directly measured these quantities, gross vehicle classification (i.e., number of axles and weight) and traffic statistics can be ascertained. Piezoelectric polymer sensors are considered, in this report, to be passive sensors since they do not generate an external field that interacts with the target of interest. Rather, they convert a mechanical force to a strain field that in turn induces an electrical voltage.

Piezoelectric polymer can be implemented to detect pedestrians, bicycles, cars, and trucks. The voltage dynamic range, or (conversely) sensitivity, can be regulated by configuring with an appropriate circuit impedance. Sensitivity is excellent, with capabilities of producing voltages ranging from millivolts to volts. Weather penetration is not a problem in the conventional piezoelectric implementations of these devices. Adverse weather conditions would degrade performance when the sensor is used as a pyroelectric.

Piezoelectric polymer sensors (composed of a transducer and support electronics that produce detections, counts, and weight measures) are inexpensive, easily installed, rugged, and reliable. A temporary installation can cost as little as $100, while permanent in-the-road installation can cost up to $800. Typical reliability ranges from 1 to 5 million axles, depending on mounting and installation. These sensors are widely in use, commercial, and off the shelf. An example of a manufacturer of piezoelectric polymer sensors is Elf Atochem Sensors, Inc. of Valley Forge, Pennsylvania, which manufactures and markets the Roadtrax Series TP™ traffic sensor. [38]

Comparison

Visible I-P-P sensors have very limited applicability because they require cooperative vehicles (i.e., head lamps permanently on). Information on the use of microwave radiometers for vehicle detectors has not been uncovered. Passive infrared point detectors have the advantage of installation above the roadway, and therefore are not subject to the same harsh treatment as sensors embedded in or on the pavement. Above-road installments are likely to be more susceptible to tampering or vandalism.

Piezoelectric polymer sensors are capable of vehicle detection, weigh-in-motion, velocity determination, and crude vehicle classification (i.e., how many axles and weight estimate). Unlike pneumatic tubes, piezoelectrics can be permanently installed. They can cover multiple lanes and discriminate between traffic in adjacent lanes by reversed polarities. None of the other I-P-P sensors offer this capability.

Infrastructure-based, point detection, active (I-P-A)

As stated above, infrastructure-based applications of sensor technology are going to be geared more toward presence detection rather than range and velocity monitoring. Active sensors, however, have range and velocity monitoring capability as a strong selling point. For the triplet, infrastructure-based, point detection, active (I-P-A) sensor, table 21 indicates six applicable sensing technologies. In each case, active sensors are implemented as point detectors. The list includes magnetic detectors, which do not fit in the context of active sensors treated above (i.e., ranging and velocity monitoring). They are considered to be active sensors from the standpoint that they create an electromagnetic field that interacts with a property of an object.

Microwave and millimeter wave

Similar in concept to the vehicle-based radar systems, microwave I-P-A sensors transmit an electromagnetic signal that interacts with (e.g., is backscattered by) a vehicle breaking the beam. In I-P-A applications, however, the active system is used as a vehicle presence detector rather than as a ranging system. Although it can be used to directly measure Doppler signature, the velocity measured will be the component of the velocity projected along the path between the sensor and the vehicle, and not the vehicle ground velocity, and thus is of very limited value. The requirements for implementing I-P-A sensors are considerably lower than for V-P-A sensors, and thus cost and widespread deployment are feasible.

Microwave vehicle presence sensors are readily available, reliable, and can be purchased for $600 to $800 per unit. They are mounted above the road, either below an overpass in a downlooking configuration, or on a post in a side-fire configuration.

Microwave Sensors of Ann Arbor, Michigan and Whelen Engineering Company of Chester, Connecticut market are two companies that offer active, microwave, vehicle-detection sensors. The TC-20 system, sold by Microwave Sensors, operates at 10.5 GHz, has an adjustable detection angle and detection pattern, and can be mounted in either an overhead or side-fire detection configuration. The unit costs $695. A microprocessor-enhanced microwave vehicle detector, the TC-26, costs $799. Whelen Engineering offers similar systems in the Tracker™ series which can be purchased from $695.

Infrared

Application of infrared laser radar to I-P-A is analogous to that presented for microwave and MMW radar in the preceding section. Road-based laser radars have been implemented both in the United States and Great Britain. Road-based sensors are manufactured by the British counterpart of Microsense. Microsense used to market the MIP active, infrared, vehicle-detector system. However, it discontinued production upon finding insurmountable problems, mainly associated with operation in inclement weather conditions. The British Trafficmaster™, real-time traffic-information system, has been installed at 115 data collection sites around Britain's M25

London Orbital Motorway, and, to the best of our knowledge, continues to use active infrared sensors. [39]

Visible

An I-P-A visible laser radar is conceivable. However, no literature has been uncovered in the searches performed to indicate any level of research or development.

Acoustic

Acoustic sensors, as discussed above, have limited applicability to vehicle-based applications. Such sensors are, however, very well suited for road-based vehicle-presence detection. Ultrasonic sensors are generally used for short-range detection purposes (i.e., presence or passage). A typical range of operation is 20 ft, at which point a beam may be 4 or 5 ft wide.

Road-based systems for vehicle or pedestrian detection applications cost about $500. Roadside ultrasonic sensors are used in Japan in a manner as ubiquitous as ILDs (to be discussed next) are used in the United States.

Historically, many problems were found in the United States with the early implementation of roadside ultrasonic sensors. Problems with salty roads, vibration, and overheating caused many agencies to preclude their further use. Perhaps less inclement weather conditions exist in Japan, which made the technology viable there. Since those times, these problems have for the most part been resolved, and now ultrasonic sensors boast an excellent record for reliability in the United States.

High wind conditions cause timing problems with the acoustic waves. There are no problems associated with elements embedded in the roadway surface. However, a gantry installation is required.

Microwave Sensors, Inc. is among many manufacturers of ultrasonic vehicle detectors. They market the TC-30 for $475, an ultrasonic sensor for detecting vehicle or pedestrian traffic, and also the TC-30C for $559, an ultrasonic, vehicle-presence detector and counter. (See references 22, 24, 30, 42.)

Magnetic

In the United States, the most prevalent technology for vehicle presence detection is the magnetic sensing device. Magnetometers and inductive loop detectors (ILD's) comprise the preponderance of vehicle detection installations. Between the two, ILD's are the most popular devices and, as such, carry a large amount of inertia into the sensing-technology decision process. Electrical current passes through a metal loop and creates a magnetic field (Ampere's Circuital Law). Eddy currents formed within the peripheral metal of a passing vehicle cause a decrease in the inductance of the loop, which exceeds the increase in inductance due to the presence of a large iron core (e.g., the vehicle engine). The passing vehicle precipitates a net decrease in the inductance of the loop, activating the detector electronics output relay. The ILD is installed within the road surface by cutting a slot 1 to 3 in deep in either a rectangular or diamond shape. Generally, the installation is 6 by 6 ft. Sealant is applied to protect the device from the environment.

ILD's are considered, in this report, to be active point presence detectors. They generate an external magnetic field, that interacts with the target to be detected. Simple detection is accomplished with a single ILD. Using microprocessor-based models and multiple sensor installations, more sophisticated traffic parameter measurement can be accomplished, such as vehicle counting, velocity determination, and vehicle classification. The *Traffic Detector Handbook* covers ILD's in detail, discussing technology, applications, design, installation, and maintenance. It also contains a section on emerging technologies.

When installed correctly, ILD's perform point presence detection tasks accurately and reliably. However, due to the nature of the installation, the device is often degraded and rendered dysfunctional by extended use. Inclement weather typically does not pose a problem to the detection process, however, snowplows can often damage the installations. Electromagnetic interference or electronic crosstalk can produce improper performance (i.e., false alarms) and therefore care must be taken to avoid these problems. Furthermore, splashover (the false detection of vehicles outside the zone of detection) can occur when ILD sensitivity is increased (i.e., to a level necessary to detect motorcycles). ILD's typically operate at frequencies between 10 and 200 kHz. Adjacent installations should operate at different frequencies to minimize crosstalk problems. In addition, installations should not be made in close proximity to large metallic structures such as bridges, that can themselves cause eddy currents to flow, thus generating a detectable signal.

Many ILD models are readily available off the shelf, including multiple channel, frequency selectable, sensitivity tunable units. Installation is expensive, tedious, and time-consuming. Caution must be exercised to apply sealant to clean, dry pavement. If installation is performed properly, reliability is good, otherwise, downtime requiring maintenance becomes the norm. Typical numbers given for the relative number of ILD's out-of-service at any one time range from 5 to 30 percent. Maintenance, when necessary, is expensive and produces an impediment to traffic flow.

Microsense Inc., 3M Safety and Security Systems Division, High Leah Electronics Inc., Sumitomo Electric U.S.A. Inc., and Saratec Traffic, among others, manufacture and market ILD detectors meeting National Electronics Manufacturers Association (NEMA) and DOT specifications. Variable sensitivities, selectable frequencies, and programmable capabilities are some of the features of these products. (See references 21, 23, 41, 42, 46, 49, 65.)

Comparison

Microwave, MMW, and infrared laser radar are all viable technologies for I-P-A applications. Microwave units are easily and inexpensively procurable. Infrared systems have been marketed, but have been found to have undesirable performance under an appreciable amount of adverse weather conditions. Active visible radars have not caught on.

The United States has chosen the ILD sensor as its traffic detector of choice, while Japan has opted for ultrasonic sensors. Ultrasonic sensors have the advantage of above-road installation and the ease of deployment and maintenance that accompanies that feature. Historically, ultrasonic sensors have had problems with weather penetration in the United States, which precluded widespread deployment. Recently, those problems have been surmounted, leaving ILD inertia as the largest remaining obstacle.

<u>Infrastructure-based, imaging, passive (I-I-P)</u>

For the triplet, infrastructure-based, imaging, passive (I-I-P) sensor, table 21 indicates two applicable sensing technologies. These systems are very complex and expensive. However, they provide continuous spatial coverage over a large region and can therefore replace multiple point detector installations.

Infrared

Thermal sensitivity and temporal frequency response are critical issues for any application and relate directly to the cooling requirements. Cryogenic cooling provides the highest performance but at the highest cost and lowest practicality. Noncooled imaging systems (e.g., pyroelectrics) are less expensive, but offer significantly degraded sensitivity. Liquid cryogens are not appropriate for permanent installations, but may suffice for demonstration equipment.

Infrared imaging sensors have the ability to provide high resolution spatial coverage of a large segment of roadway. Although such systems are very expensive, they may be feasible given the large number of point presence detectors they could conceivably replace. No work has been found published on applying infrared I-I-P sensors to traffic surveillance. However, their visible counterpart has demonstrated success, as will be discussed next.

Visible

The Wide Area Detection System (WADS) of the 1970's and its following effort, the Video Detection System (VIDS) are infrastructure, vision-based, traffic-monitoring systems that have been utilized to determine vehicle presence and passage and traffic flow parameters such as volume and occupancy. VIDS incorporates real-time data analysis techniques to calculate traffic statistics at a user-selectable region within the video camera's field of view. Processing is quickly taken out of the image domain and into the feature (detected vehicles) domain for statistical data and derived quantities such as vehicle velocity.

Most likely an interested customer would procure the image processing algorithms and then interface them with a separately purchased video camera. Much cost data has been uncovered for both the image processor and the camera. The image processing algorithms must be very high level and capable of treating phenomena associated with daytime travel (e.g., shadowing, solar glints and phenomena specific to nighttime operation (e.g., headlights, non-uniform lighting conditions). It is currently an expensive installation, due to limited market penetration, however, it can replace multiple single point presence detectors (e.g., ILD's), while simultaneously offering superior capabilities for determining higher level traffic flow parameters. In addition, the processors must treat the same potential problems associated with all sensing, namely obscuration effects and environmental variations. Installations are portable and deployable above the road, and therefore do not impose an impediment to traffic flow. The VIDS has been successfully demonstrated for a variety of roadway, environmental, and traffic conditions.

The University of Minnesota developed the first real-time version of VIDS. Detailed studies of passive-visible, infrastructure-based, traffic-surveillance systems have been conducted by Cal Poly and the Environmental Research Institute of Michigan. The prototype systems that evolved from the studies are being extensively tested in IVHS operational field tests such as FAST-TRAC, being conducted in Oakland County, Michigan. (See references 27, 33, 34, 42, 48.)

Comparison

Visible I-I-P systems do not require cooling to obtain sufficient sensitivities for traffic surveillance applications. Infrared I-I-P systems must be cooled. Visible I-I-P systems have a lower cost for the sensors. The image processing packages, however, are very expensive. Infrared I-I-P systems have not been implemented to date. It is believed that the image processing packages necessary for such systems would also be complex. They would be less complex, however, than visible I-I-P systems due to the nature of the signatures involved. The visible reflective signature is subject to much greater variation, shadowing, head lamps, etc. The infrared emitted signature would undergo contrast reversals, but in general, would have much less signature variation. Infrared systems would likely provide superior weather penetration capabilities.

Infrastructure-based, imaging, active (I-I-A)

For the triplet, infrastructure-based, imaging detection, active (I-I-A) sensor, table 21 indicates one applicable sensing technology. A demonstration system has been proposed by UMTRI and the Environmental Research Institute of Michigan (ERIM) and funded by the National Highway Traffic Safety Administration (NHTSA). The program will be discussed as the only known I-I-A application approached to date. [66]

Infrared

In an active optical-imaging system, a laser beam is scanned in sequential order (i.e., row-by-row) to incrementally measure returns from each area within a scene of interest. In this manner, a scene is divided into many resolution elements for which range and reflectance are measured for each resolution element, and therefore, two perfectly registered images of a scene (i.e., range and reflectance) are generated. The range image can then be used to directly determine object sizes and locations. Generally, the reflectance image is utilized in the image/data processing to clarify ambiguities or inconsistencies in the range imagery.

ERIM is the original developer of 3-dimensional laser radar imaging systems. Quantitative characterization of the vehicle motion environment will be accomplished using a suite of laser radars deployed on 100 ft-high towers. Vehicle dynamics, tracks, and intervehicle dependencies will be quantified to a very high level of accuracy. For each vehicle passing the system, a track file containing vehicle centroid and yaw estimates will be compiled in real time.

Miscellaneous technologies for monitoring driver condition

Regardless of how many safety features are incorporated in the infrastructure and vehicle, current safety ultimately requires man-in-the-loop operation. Safety is, therefore, limited by the driver's ability to accurately perceive the surrounding scene. The safety features discussed in this paper are related to expanding the driver's capability to sense the immediate environment. Night vision systems extend driver visual capability, as do blind-spot object detectors and lateral and longitudinal controllers. Safety systems rely on driver ability to respond to the information acquired from both his sensory perception and from vehicle-based sensors. An impaired driver, either under the influence of drugs, alcohol, or fatigue, will have difficulty responding readily to these stimuli, and thus poses a safety hazard to himself and others.

Driver-eye-movement information has been shown to be an accurate indication of impairment. Numerous techniques have been developed over the years to monitor driver condition. Much of the eye-movement research has been explored for application to vehicle driver monitoring. Unfortunately, most of the eye movement monitoring techniques are impractical in nature. They impose unrealistic requirements such as stationary head position, electrodes, and obtrusive equipment. Eye movement must be decoupled from head movement. ERIM proposed a system that used an active infrared beam deflected by a diachronic rear-view mirror to monitor eye point-of-gaze direction, while determining driver head position by measuring an unfocused image with a quad detector. Other driver characteristics such as brain waves, heartbeat, and skin resistivity have also been correlated with the impairment condition.

An alternative to directly measuring a physical characteristic of the driver is to monitor multiple conditions within the vehicle to infer driver fatigue. It has been noted that steering wheel movements are highly correlated with driver fatigue. An alert driver demonstrates smooth, continuous steering motions, while a fatigued driver will demonstrate long periods of no steering wheel motion, followed by large jerky movements. Such a condition, however, is easily detectable. False alarms can occur during sharp turns. Coupling steering-wheel motion to other vehicle parameters such as windshield-wiper state, lights state, travel speed, turn signal state, clock, or odometer, a microprocessor based algorithm can discern between degraded driving behavior due to poor driving conditions (e.g., poor visibility) and driver fatigue.

Nissan has developed a Safe Driving Advisor using the above criteria. This system has demonstrated, through simulators and specially equipped vehicles, the capability to discriminate between driver alertness and driver fatigue.

Cost, availability, and reliability information are not available regarding the Nissan system. Current eye monitoring systems, that have been developed as research tools are prohibitively expensive, generally costing more than the automobile itself. There are many manufacturers of the various eye-monitor systems. Vehicle-based, driver-condition monitors, however, are currently in the research phase. (See references 16, 17, 29, 71.)

Weather monitoring

The determination of a safe driving speed is a complicated function of road curvature, driver response time, and the motion of other vehicles in the vicinity (i.e., headway control). In addition, prevailing weather limits (e.g., fog or precipitation) the safe vehicle-operating envelope, primarily by restricting operator vision and directly altering vehicle dynamics through degraded road surface conditions (rain, sleet, ice, or snow) and strong winds. Knowledge of the existence of such conditions can directly aid in the determination of a safe driving speed. Weather sensors measuring wind speed and direction, precipitation, air temperature, and relative humidity can be installed in roadside configurations to determine potentially hazardous weather conditions. In addition, sensors embedded directly in the pavement, with thermal inertia properties matched to the pavement itself, can be installed to directly measure pavement temperature and amount of salt or chemicals on the surface. In this manner, the road surface coefficient of friction can be estimated.

Optical technologies applied to measure or infer loss of visibility include nephelometry, transmissometry, LIDAR, and radiometry. A nephelometer illuminates a small sample volume internal to the instrument and measures either the total amount of light scattered (integrating overall solid angle), or the amount of light scattered in particular directions. The volume scattering coefficient is retrieved from the measurement and allows transmission as a function of range to be inferred. The measurement is insensitive to absorption so that transmission may be underestimated for urban hazes with significant absorbing components (e.g., soot). Because nephelometers sample a very small atmospheric volume, the representativeness of the measurement relative to a geographic area is always a concern.

Transmissometers typically employ a source of modulated radiation viewed by an optical receiver through a path whose optical length is selected based on the visibilities of interest. A modulated source allows rejection of path radiance signals so that transmission is measured directly. Transmissometers have the advantage of performing a path-integrated measurement over a (typically) more representative volume; disadvantages include the need for a two-ended measurement resulting in increased system complexity.

A LIDAR (light detection and ranging) system transmits pulsed or modulated energy and detects the backscattered signal. Inversion algorithms are used to extract transmission based on assumptions about the atmosphere's optical properties or spatial structure. LIDAR,s are typically very complicated and expensive instruments suited for central rather than highly distributed siting; eye safety is also a significant issue. However, modifications of hand-held laser range-finder hardware for visibility-measurement applications illustrating the potential for at least moderate cost implementations have been demonstrated.

Optical radiometers simply measure luminance at the sensor aperture. When combined with a suitable target (e.g., black/white panel of known reflectance and known inherent contrast), a calibrated radiometer can be used to measure contrast transmittance directly. The method requires remote measurement of the target and background luminance to obtain the apparent target contrast; contrast transmission is retrieved by ratioing the measurement to the known target inherent contrast. Lighted panels are required at night; a concern of the method is maintenance of the target to preserve the expected inherent contrast. An advantage of the method is direct recovery of contrast transmission; measurements related to transmission alone require additional modeling and assumptions to estimate visual performance.

Standard meteorological instrumentation is available to identify wind hazards. As an example, an icing detector developed by NASA for aircraft applications is suitable for monitoring the accretion rate and total amount of ice deposited in sleet storms. Sonic anemometers are highly accurate, commercially available, wind-speed measuring devices requiring high power and high cost. A vortex anemometer is a cylindrical body with no moving parts, however the casing must be aligned with the wind direction using a vane and thus leading to long response times. A propeller anemometer is a simple device that relates wind speed to the rotation frequency of a propeller. Two orthogonal propellers can be configured to measure axial components of wind speed and thus avoid the requirement to align the device with wind direction. Hot wire or hot film anemometry involves the calculation of wind speed through measurement of the cooling of an electrically heated metallic wire or film. Laser anemometry involves focusing laser light onto a small volume, thus creating interference fringes. The spatial distribution of the interference fringes provides a very precise measure of wind speed. High complexity and cost, however, preclude near-term widespread deployment. These techniques have been implemented in varying degrees in infrastructure-based installments. Vehicle-based applications would provide a probing capability, and research has begun in this area under the European DRIVE program.

Standard meteorological instrumentation is also available to measure precipitation and temperature in order to detect unfavorable road conditions. The reduction in traction caused by snow cover and water or ice films is a fundamental limiting factor for safe vehicle operation. Passive remote sensing (radiometry) cannot directly determine the reduction in traction, but can potentially determine the presence of traction-reducing films.

A passive radiometer viewing the road surface can potentially measure apparent brightness, color (spanning wavelengths from ultraviolet to microwave), and polarization to detect changes in the surface condition. Imaging radiometers add spatial characterization (such as texture) to distinguish surfaces. The technique is not unlike satellite remote-sensing technologies that use brightness and color to indicate properties such as soil, crop, and land-use classifications.

Differences in all the properties mentioned above will be available to distinguish the materials in question. Research has found that bright snow completely obscures the road while the water suppresses the inherent road signature without eliminating it.

Beyond determining the general road surface condition (e.g., wet or dry), passive sensing also has the potential for estimating the thickness of the precipitated layer. One way to do this is to find a spectral region where the layer progresses from transparent to opaque for thicknesses of interest. If a target with known signature (e.g., areas of different color or brightness) is placed on the road surface, attenuation of the signature can potentially be related to the depth of the layer. There are complications due to first-surface effects of the layer on the observed signature (generally unrelated to film thickness), film impact on the known signature being observed, and contamination of the film (e.g., dirt) changing its volume attenuation properties. The severity of these problems in the current application would, in part, determine whether active-sensing techniques are required to detect water or ice coating thickness.

Sensor fusion has been invoked to team technologies in a complimentary manner. For example, an active infrared sensor can differentiate between dry, moist, wet, snowy, and icy conditions, while a moisture sensor embedded in the pavement provides depth of accumulation information. The European DRIVE program CROW replaces the in-pavement moisture depth sensor with an above-ground microwave sensor capable of determining accumulation depths. The CROW project has also developed a laser-based imaging system to aid in surface condition assessment. The proponents of this technique are envisioning vehicle-based implementations.

Roadside-based weather sensors reportedly promise to save 10 percent, approximately $200 million each year, on snow and ice removal costs in the United States. Vehicle-based weather sensors could be used to monitor ambient conditions, but would lack the additional information provided by embedded sensors. Vehicle-based weather sensors are currently in the developmental phase, while infrastructure-based implementations can provide additional information to aid in a determination of driving conditions within some accuracy and cost limitations.

Roadway surface condition, weather condition, visibility, and wind-speed monitoring systems are available commercially from numerous vendors in the United States and abroad. Surface Systems, Inc. markets a system consisting of four pavement sensors, a weather station and a central computer costing approximately $35,000. They have installed 1100 sensors for over 100 agencies, demonstrating a good record of reliability. Climatronics markets the FRENSOR, which is an active device that directly measures the freezing point rather than estimating it, as do many other sensors. Vaisala of Finland produces the DRS12 passive temperature sensor. The device monitors surface and below-surface temperatures to rate road conditions. AANDERAA Instruments markets road-surface temperature and conductivity sensors. Some other suppliers of visibility, nephelometry, anemometry, and pavement sensors are Findley Invine of Scotland, BG Engineering of Holland, Rails Company of Sweden, Vibometer SA and Boschung Mecatronic of Switzerland, Hokkaido Development Bureau of Japan, and Schrack Systems Inc. of Austria.

In addition to these products, major developmental efforts are underway under the European DRIVE program CROW and its successor in DRIVE II, GERDIEN.[53,56]

FUNCTIONAL/PERFORMANCE REQUIREMENTS

This section addresses the mapping of countermeasure functions into requirements for sensing, processing, communication, and display. Each countermeasure and candidate sensing technologies have been described in detail. This section bridges the gap between countermeasure functions and applicable technologies by describing the measurement requirements necessary to support each countermeasure function. Matrices are included that illustrate that the relationships between countermeasure functions and measurement functional requirements, and also between measurement functional requirements, and technologies.. These relationships are complicated by the fact that there are many-to-one and one-to-many correspondences between countermeasure functions, functional requirements and technologies. This does have the advantage, in many cases, of offering the designer many implementation alternatives.

The nineteen countermeasure functions are individually described in the following section from the perspective of the sensing functional requirements that each imposes. Applicable sensing technologies will be mapped to countermeasure functions via functional requirements in a matrixed approach. Processing, communication, and display will be treated as separate sections. However, the countermeasure functions for each will be treated collectively.

Sensing Requirements

As previously stated, sensing technology will constitute the preponderance of this report. To facilitate treatment of the diverse sensing issues involved in AST, two matrices will provide the focus for discussion throughout this section. Table 23 shows a matrix of the interrelationships among sensing functional requirements and countermeasure functions. Each row, denoted CMi (i=1...19), is associated with one or more columns, denoted FRj (j=1...12), by an X, where CMi denotes the i^{th} countermeasure function and FRj is the j^{th} functional requirement. Each X signifies that the data required by the countermeasure function can be provided, in part or in whole, by the corresponding functional capability, which in turn becomes a functional requirement for sensing.

Table 23. Sensor functional requirements applicable to each countermeasure function matrix.

	FR1	FR2	FR3	FR4	FR5	FR6	FR7	FR8
CM1						X		
CM2							X	
CM3								X
CM4								X
CM5			X			X		
CM6			X			X		
CM7								X
CM8			X					
CM9	X	X						
CM10			X		X			
CM11			X		X			
CM12	X							
CM13	X							
CM14						X		
CM15	X	X		X				
CM16	X	X						
CM17	X	X						
CM18	X	X		X				
CM19	X		X					

FR1 - Presence detection
FR2 - Entrance/exit detection
FR3 - Range monitoring
FR4 - Velocity measurement
FR5 - Velocity monitoring
FR6 - Vision enhancement
FR7 - Driver condition monitoring
FR8 - Weather monitoring

CM1 Night vision perceptual enhancement for dark/unlit situations
CM2 Driver impairment warning for erratic behavior
CM3 Vehicle-based friction/ice detection and warning system
CM4 Roadside friction/ice detection and warning system
CM5 Lateral lane edge detection warning and steering correction
CM6 Lateral lane edge detection warning and steering correction with preview
CM7 Dynamic horizontal curve speed advisory and control
CM8 Longitudinal control for objects in the roadway
CM9 Presence of pedestrians at midblock crosswalks
CM10 Headway control based upon adaptive cruise control
CM11 Short headway time and/or distance warning
CM12 Warning of the presence of oncoming vehicles (cooperative vehicles)
CM13 Warning of the presence of oncoming vehicles (road-based system)
CM14 Lane-keeping using a detectable line in the center of the lane (virtual monorail)
CM15 Warning of the presence of vehicles on a major road (15a & b stop and yield)
CM16 Warning of the presence of vehicles on a minor road
CM17 Cooperative intersection - four-way stop right-of-way indicators
CM18 Approaching vehicle warning for driver making a left turn/also warnings of a vehicle turning left
CM19 Detecting obstacles in blind spot

In an analogous manner, table 24 relates each sensing functional requirement, denoted FRi, to a specific sensing technology, denoted Tj (j=1...9), capable of providing the necessary information. There can often be a many-to-one or one-to-many mapping, and multiple technologies can often be used individually or jointly with others to implement countermeasure functions.

Table 24. Current technologies that address each functional requirement matrix.

	T1	T2	T3	T4	T5	T6	T7	T8
FR1	X	X	X	X	X	X		
FR2	X	X	X	X	X	X		
FR3	X	X	X					
FR4	X	X	X		X	X		
FR5	X	X	X					
FR6		X	X					
FR7		X					X	
FR8		X	X	X				X

T1 Microwave or MMW
T2 Infrared
T3 Visible
T4 Acoustic
T5 Magnetic
T6 Piezoelectric
T7 Miscellaneous technologies for monitoring driver condition
T8 Weather monitoring equipment

FR1 Presence detection

FR2 Entrance/exit detection

FR3 Range monitoring

FR4 Velocity measurement

FR5 Velocity monitoring

FR6 Vision enhancement

FR7 Driver condition monitoring

FR8 Weather monitoring

As an example of the methodology of interpreting the matrices, countermeasure function 10 (CM10), headway control, can be addressed either by directly measuring the relative velocity between two vehicles via the Doppler signature, functional requirement number 5, FR5, or alternatively, by monitoring the range between the two vehicles as a function of time, FR3. Using the former method, relative velocity is ascertained instantaneously while the latter method requires multiple range measurements. FR4, velocity measurement, is not applicable to this countermeasure function because it is a solitary velocity measurement, whereas CM10 requires continuous velocity monitoring. Table 24 shows that any of the ranging or velocity monitoring radar technologies (e.g., infrared, microwave) would be applicable. Choice of the appropriate one would involve an application-specific tradeoff analysis, giving consideration to weather penetration, resolution, cost, size, reliability, etc.

The remainder of this section will associate each countermeasure function with corresponding sensing technologies via the functional requirements that each countermeasure function dictates. This mapping will be accomplished by describing all functional requirements that address each countermeasure function and the sensing technologies by which they are satisfied.

Countermeasure function 1, night vision enhancement for dark/unlit situations

CM1 can practically be addressed solely by FR6, vision enhancement. It is conceivable that night vision would be enhanced by an active imaging system such as radar or microwave radar, using a sophisticated target detection system to locate objects ahead and superimpose these object locations in a projected image overlaid on the scene viewed by the driver (e.g., head-up display, HUD). These approaches, however, lack practicality in the context of cost-effective, vehicle-based safety features. They require sophisticated real-time data processing and sensor fusion algorithms that, from a cost and implementation standpoint, would prohibit implementation in the near term. Vision enhancement, however, using passive infrared imagers or extremely sensitive passive visible cameras, is within the grasp of current technology and is likely to become cost-effective for vehicle-based installations in the near term. In table 24, we indicate that there are two candidate technologies—T3 (infrared) and T4 (visible) that are capable of greatly enhancing night vision, and either could be implemented to completely achieve CM1. Many human factors issues are involved, the knowledge of which is critical to successful implementation of such a countermeasure. From a purely functional standpoint, either passive infrared or visible technology would be suitable. High-performance imaging infrared systems likely need cooling while high-sensitivity visible systems likely require expensive, image-intensifier electronics. At present, these systems are very expensive, presenting the prime impediment to widespread deployment. Imaging infrared systems based on pyroelectric technologies are being evaluated for automotive applications, but at some sacrifice in performance (i.e., thermal sensitivity and temporal frequency response). In their favor, however, pyroelectric infrared systems are significantly less expensive and more reliable than those cryogenically cooled.

Countermeasure function 2, driver impairment warning for erratic behavior

CM2 necessitates its own functional requirement, FR7—driver condition monitoring. As discussed in chapter 2, approaches for monitoring driver condition are numerous and diverse. The most desirable approaches involve either monitoring a feature (heart rate, skin resistivity, eye movement) of the driver, or monitoring the actual vehicle by coupling erratic or unnatural steering behavior with the status of current equipment (turn signal, speedometer, windshield wipers, clock). Table 24 indicates this correspondence and also eludes to the eye movement monitoring technique using an infrared beam, as discussed in chapter 2. As in CM1, human factors issues dominate concern for these implementations. Monitoring must be done unobtrusively. In addition, interpretation of the sensed data requires human factors knowledge.

Countermeasure functions 3 (vehicle-based) and 4 (roadside, friction/ice detection, and warning system)

As depicted in table 23, CM3 and CM4 dictate an identical functional requirement—FR8, weather monitoring. Table 24 indicates that weather sensing can be accomplished by a combination of weather monitoring equipment (T8) and infrared and microwave technology (T3 and T5). Conceivably, both countermeasures can be addressed by instruments capable of monitoring ambient conditions (temperature, humidity, pressure, and precipitation). In an implementation such as this, road surface condition is not measured directly, but is inferred from prevailing conditions. A remote weather sensor, microwave- or infrared-based, could similarly be implemented either roadside or vehicle-based. The vehicle-based implementation is unlikely to be viable due to cost considerations unless the vehicle was already equipped with infrared or microwave devices to meet the requirements of other countermeasure functions. In this area, no evidence has been found to indicate that research and development activities have been initiated. A system that directly measures the material characteristics of the surface, such as the SCAN16 system described in chapter 2, can currently only be implemented in a roadside scenario. Major research efforts are currently underway to assess driving conditions from the infrastructure, such as the European DRIVE I CROW program, and its successor, ROSES, in DRIVE II.

Countermeasure functions 5 and 6, run-off-road and lateral lane-edge detection warning and steering correction without or with preview

CM5 and CM6 are satisfied by the same set of functional requirements, FR3 and FR6. Both countermeasures require knowledge of the lateral vehicle offset from the lane edge. CM6 requires, in addition, longitudinal measurements to the lane edge for curved roadways. Functional requirements 3 and 6, range monitoring and vision enhancement, are complementary and either one or both could be used to implement CM5 and CM6. Table 24 shows that any of the active ranging technologies and the vision enhancement technologies, such as microwave or MMW (T1), infrared. (T2), or visible (T3), are applicable. The description of these countermeasures discussed previously stipulates that the lane edge will be made cooperative in some manner to enhance the signature measured by any one of the active ranging sensors. It is believed that from a sensing perspective, cooperative roadside beacons, either passive or active, are necessary for realizing cost-effective sensing systems. The method of enhancement would depend on which active ranging method was implemented. It is conceivable that the cooperative lane edges could themselves be transmitters encoding the necessary information into a signal that could be sensed by a vehicle-based passive sensor.

Countermeasure function 7, dynamic horizontal curve speed advisory and control

CM7 is no different from a sensing-functional-requirement viewpoint than CM3 or CM4, and thus can be satisfied by FR8. Again, table 24 shows the applicability of conventional weather monitoring devices (T8), as well as other sensing technologies (e.g., infrared, microwave, and acoustic) that have been used to acquire weather information. The radius of curvature and superelevation of each curve, as described in the countermeasure statement, is surveyed prior to system installment, and thus the only dynamic (i.e., time varying) variables are the road surface and visibility conditions. The systems proposed for CM3 and 4 will also satisfy CM7 from a sensing standpoint.

Countermeasure function 8, longitudinal control for objects in the roadway

CM8 requires the range monitoring functional requirement FR3. A vision enhancement technology would be insufficient for meeting the requirements of this countermeasure function because range information, in addition to object detection, is required. Any technologies indicated in table 24, such as laser (T2 or T3) or microwave or millimeter wave radar (T1), would be appropriate to perform range monitoring. In favor of microwave or MMW radar would be the excellent weather penetration capabilities. This countermeasure is likely to be needed most under conditions of reduced visibility such as nighttime or inclement weather conditions.

Countermeasure function 9, presence of pedestrians at mid-block crosswalks

CM9 can be addressed at a minimal level by sensing FR1, presence detection, or at a higher level by FR2, entrance/exit detection. Table 24, being so broad in scope, indicates many possible technologies. The most viable technology candidates to address this countermeasure, however, are piezoelectric polymer (T6), and passive infrared (T2). The piezoelectric polymer implementation would sense the weight of a pedestrian standing in the ped-port waiting to cross the road. A pyroelectric or infrared sensor would detect the difference in thermal signal associated with a pedestrian in the region of interest. A sensed pedestrian would trigger the warning signal on the active road sign. The warning signal would remain on for a period of time allowing for safe crossing. Two sensors, either piezoelectric or pyroelectric, would be useful for detecting the entrance and exit of a pedestrian crossing a roadway. Again, the entrance detector would activate the active road sign. In this case, however, the road sign would cease its active warning upon receipt of a signal from the exit detector, indicating a successfully completed crossing. A simple counter could be implemented for instances of multiple pedestrians crossing concurrently. To insure additional safety, an area detector (perhaps ultrasonic) covering the entire crossing region could survey the area to confirm the presence or absence of pedestrians.

Countermeasure functions 10 and 11, headway control based on adaptive cruise control and short headway time and/or distance warning

Table 23 shows that CM10 and CM11 can be implemented either with a range monitor (FR3), or with a velocity monitoring system (FR5). Table 24 indicates the related range and velocity monitoring technologies, microwave-MMW (T1), infrared (T2), and visible (T3). A velocity monitoring system, such as a Doppler radar, can measure directly the instantaneous velocity difference between a leading and following vehicle. The adaptive cruise control of the following vehicle is automatically set to the velocity of the leading vehicle. Using a range monitoring system, relative velocity between the vehicles can be measured by calculating closure rates based on sequential range measurements. Any of the pulsed or continuous-wave radar technologies would be capable of meeting the requirements of this countermeasure function. Sensor tradeoffs between cost, weather penetration, and accuracy would need to be performed.

Countermeasure function 12, warning of the presence of on-coming vehicles (cooperative vehicles)

CM12 requires FR 1, presence detection. Table 24 indicates multiple possible presence detection technologies. Only one, however—visible (T3)—is relevant to this countermeasure description. The key words being "cooperative vehicles." Other technologies are applicable, though they do not specify the cooperative requirement. As presented in chapter 2, a sensor operating in the visible portion of the electromagnetic spectrum can sense headlights of an on-coming vehicle. Once sensed, a warning signal, in the form of light beacons, is transmitted to traffic traveling in the opposite direction. The visible sensor must be capable of discriminating headlights from other forms of light while avoiding imaging. Discrimination could be performed based on the spectral signature, rather than spatial signature, of headlights. Perhaps selected narrow bandwidth filters would be applicable, or a specific modulation (i.e., flashing) in the ultraviolet signature, that would be unobserved by drivers of on-coming vehicles.

Countermeasure function 13, warning of the presence of on-coming vehicles (road-based system)

CM13 can also be addressed with FR1, presence detectors. Although, in this case cooperative vehicles are not required. A simple microwave (T1), infrared (T2), acoustic (T4), magnetic (T5), or piezoelectric (T6), sensor can detect a vehicle passing over it or within its region of coverage (e.g., field-of-regard). Upon detection, a signal is transmitted to a roadside warning sign to indicate the presence of on-coming vehicles.

Countermeasure function 14, lane-keeping using a detectable line in the center of the lane (virtual monorail)

CM14 can conceivably be addressed by a number of technologies. The key term in the countermeasure function statement is "detectable," indicating that some form of signature enhancement, either passive or active, will be employed to make the centerline easy to detect. This enhancement could be a special paint containing metallic filings (magnetic detection (T5), high spectral reflectivity (visible detection (T3), or emissivity contrast (infrared detection (T2). A linear array of sensors positioned along the lateral dimension of the vehicle would serve to detect the instantaneous position of the vehicle relative to the centerline.

Countermeasure function 15, warning of the presence of vehicles on a major road

CM15 can be addressed at varying degrees of complexity. The most rudimentary implementation of an operational system would incorporate a single presence detector (FR1: any of the ones discussed above (T1 through T6), while a more advanced system would employ entrance/exit detection (FR2) or infrastructure-based velocity measurement (FR4). A single presence detector would have to be located at a position far enough down the major roadway to provide sufficient warning to drivers on the minor road. A warning signal would be activated and would continue until a preset period of time had elapsed. The position of the detector must provide sufficient time to warn of vehicles traveling at excessive speeds, while the time duration of the warning must provide sufficient time for slow-moving vehicles to traverse the stretch of roadway. This approach is the least expensive. A tremendous price is paid, however, in the form of perceived safe time for a vehicle on the minor road to perform the necessary maneuver. For example, consider a roadway with a design speed of 40 mi/h. A zone such as this is likely to have vehicle speeds varying from 20 mi/h to 60 mi/h. A detector should be placed down the road far enough to provide sufficient warning for a vehicle traveling at 60 mi/h, and the warning duration should coincide with that necessary for a 20 mi/h velocity vehicle to safely exit the stretch of roadway. Using two presence detectors, for either entrance/exit (FR2) or velocity measurement (FR4), alleviates these constraints by designing to individual vehicle dynamics rather than to an operational envelope based on long-term averages. For the entrance/exit scenario, each time an entering vehicle is detected, the warning signal is activated until the vehicle is detected upon exiting. Multiple vehicles detected upon entering would increment a counter while exiting vehicles would decrement the counter. The warning signal would cease when the counter reached zero.

Two position sensors located near the entrance could estimate velocity on an individual vehicle basis and set the warning signal timer accordingly.

Countermeasure function 16, warning of the presence of vehicles on a minor road

CM16 can also be addressed by multiple presence detectors (FR1, FR2, or FR4). A four-way intersection will need at least five sensors, while a three-way intersection would require four sensors. Any of the presence detectors (T1 through T6), may be used to detect vehicles stopped and waiting to enter the intersection. A remote, probably downlooking, presence sensor would be necessary to detect vehicles within the intersection. Either single presence detectors could be located down the minor road to detect approaching vehicles and activate the warning signal in the event of a possible conflict, or multiple sensors could be employed to estimate the velocity of the vehicle traversing the minor road, and therefore more reliably assess the possibility of conflict.

Countermeasure function 17, cooperative intersection —four-way stop right-of-way indicators

CM17 is a road-based system that utilizes the same technologies as CM16 above. Any of the presence sensors previously discussed can be used to detect stopped vehicles awaiting the signal to proceed with their maneuver. Either an area presence detector (above road-mounted) covering the intersection or exit presence detectors can be implemented to sense that the intersection is free from vehicles and prepared for the next maneuver.

Countermeasure function 18, approaching vehicle warning for driver making a left turn/also warnings of a vehicle turning left

CM18 is also a road-based system that can be implemented at various levels of complexity. The first part of the countermeasure function statement is identical from a technology standpoint to CM15 (i.e., it necessitates FR1, FR2, or FR4), and has the same considerations regarding individual versus operational envelope treatment. Handling a left-turning vehicle ahead requires presence detection at a minimum, and likely should also require velocity or deceleration detection. In order to achieve the forewarning required to change lanes by vehicles behind a left-turning vehicle, it is desirable to detect the left-turning condition prior to the turning vehicle stopping. This requires multiple position sensors (two for velocity, three for deceleration) in order to provide sufficient notice.

Countermeasure function 19, blind spot near obstacle detection

Table 23 indicates that presence detectors (FR1) and range sensors (FR3) are applicable to CM19. For this countermeasure, detection within a specified field-of-regard (i.e., blind spot detection or backing-up maneuvers) is desired. Ultrasonic sensors (T4) or sensors operating on radar principles (T1, T2, or T3) are excellent for detecting an object that has encroached upon an unsafe region relative to the equipped vehicle.

Processing requirements and technology assessment

This section discusses the processing criteria associated with the sensor technology functional requirements necessary to achieve the aforementioned safety countermeasures. Figure 58 lists the eight sensor technology functions along with a fundamental description of data processing requirements specific to that function. The data processing requirements vary in complexity with sensor technology and countermeasure implementation. For example, the functional requirement of presence detection for the countermeasure of detecting pedestrians at a mid-block crosswalk may simply need a processor to make a straightforward logical decision based on monitoring a single sensor output. On the other hand, the task of range monitoring for lateral lane-edge detection warning and steering correction may require the processor to fuse data from multiple sensors and perform mathematical computations on that data in order to produce time-critical signals for vehicle control systems. In all cases, the processing issues that must be addressed are performance (i.e., instruction execution rate), input/output capacity, cost, and reliability.

Functional Requirement #1: PRESENCE DETECTION

Applicable to:	Pedestrian Presence	Presence of On-coming Vehicles
	Presence of Vehicles on Major/Minor Roads	
	Cooperative Intersections	Left-Turn Warnings
	Blind Spot Detection	
Viable Technology:	Piezoelectric Polymer	Inductive Loop or Magnetometer
	Passive IR	Radar
	Microwave or MMW Radar	Sonar/Ultrasonic/Acoustic Radar

Processing: All sensor technologies provide a simple present/absent signal to the processor that must either use that data to activate a warning device or fuse it with other sensor data.

Communications: Either dedicated or local transmission between sensor/processor/ indicator device (intra-vehicle, vehicle-to-roadside, roadside).

Functional Requirement #2: ENTRANCE/EXIT DETECTION

(As above except more localized, i.e., point sensing.)

Functional Requirement #3: RANGE MONITORING

Applicable to:
Lateral Lane Edge Detection Warning and Steering Correction
Longitudinal Correction for Objects in Highway
Headway Control Based on Adaptive Cruise Control
Short Headway Time/Distance Warning
Blind Spot Detection

Viable Technology:	Radar	Microwave or MMW Radar

Processing: Simple mathematical computations/scaling to determine range to roadside or object (using pulsed or FMCW signals) and logical limit comparison to activate warning/correction system (20-Hz rate). Also, correction system control signal processing for braking, acceleration, and steering.

Communications: Dedicated lines of control for warning/correction devices (unless roadside transducers are used to encode road information; then digital data packets must be passed).

Figure 58. Summary of processing and communication requirements.

Functional Requirement #4: VELOCITY MEASUREMENT

Applicable to:	Warning for Vehicle Presence on Major Road (Velocity Info) Left-Turn Warnings Viable Technology: Piezoelectric Polymer Inductive Loop or Magnetometer Passive IR Microwave or MMW Radar
Processing:	(1) Using all technologies above, temporal differences in range can produce velocity, or (2) Using radar technologies, Doppler frequency processing produces velocity. These velocities are fused with other data and simple decisions are made.
Communications:	Dedicated lines of control for warning devices or local transmission links (intra-vehicle, roadside).

Functional Requirement #5: VELOCITY MONITORING

Applicable to:	Headway Control Based on Adaptive Cruise Control Short Headway Time/Distance Warning Viable Technology: Ladar Microwave or MMW Radar
Processing:	(1) Range determination from mathematical computations/scaling and temporal samples of range to determine closing rate (relative velocity), or (2) Processing of Doppler frequency to determine relative velocity. Fusion of velocity with other information (i.e., range) and simple comparisons to decide whether to activate warning/correction systems.
Communications:	All dedicated in-vehicle control (intra-vehicle).

Functional Requirement #6: VISION ENHANCEMENT

Applicable to:	Night Vision Enhancement Lateral Lane-Edge Detection Warning and Steering Correction Lane-Keeping Using Detachable Lane Line	
Viable Technology:	Passive Infrared	Passive Visible
Processing:	Imaging processing and simple mathematical computations to trigger obstacle avoidance warning.	
Communications:	Dedicated data path for image display unit (possible HUD) (intravehicle).	

Figure 58. Summary of processing and communication requirements (continued).

Functional Requirement #7: DRIVER CONDITION MONITORING

Applicable to:	Driver Impairment Warning for Erratic Behavior
Viable Technology:	Driver Condition Monitoring Technologies
Processing:	Fusion of multiple sensors (speed, brakes, steering, etc.). Simple decision-making based upon monitoring device output. Output would activate a warning device (i.e., erratic behavior warning) or prohibit vehicle operation.
Communications:	Dedicated control of warning devices and vehicle enable/disable systems (intra-vehicle).

Functional Requirement #8: WEATHER MONITORING (ROAD CONDITIONS)

Applicable to:	Vehicle/Roadside-Based Friction/Ice Detection Warning Systems
Viable Technology:	Weather Sensor (temperature, humidity, pressure, precipitation)
Vehicle-Based Processing:	Fusion of sensor data to determine conditions. Simple math to determine advisory speed and speed comparisons to enable warning devices.
Communications:	Dedicated control of warning/advisory devices (intra-vehicle).
Infrastructure -Based Processing:	Same as vehicle-based but advisory speed and warnings are displayed on roadside signs (not in vehicle).
Communications:	Dedicated wiring or local transmitters/receivers between sensors/processor/display signs. Low speed, low throughput, low bandwidth, low power (roadside, vehicle-to-roadside).

Figure 58. Summary of processing and communication requirements (continued).

In this discussion we are assuming that the sensor hardware will be providing the processor element with signals (data) in a ready-to-use format. For example, if we are considering a frequency-modulated continuous wave (FMCW) radar sensor for the purpose of measuring range, it is assumed that the sensor hardware performs Fast Fourier Transform (FFT) on the raw data and provides the processor with frequency information that is proportional to range. This is a reasonable assumption since versatile/programmable high-speed signal processing hardware is now common and available at a reasonable cost. However, as cost, size, and performance tradeoffs are evaluated during any active countermeasure system design phase, partitioning of tasks may be shifted between sensor hardware and processor software/hardware. In other words, for the example above, it may be more desirable to perform the FFT in the processor software rather than in the sensor hardware.

In general, the processor performs simple mathematical computations (which may be part of an algorithm) and/or makes logical decisions to generate control signal parameters for action to be taken by the rest of the system. We will start by considering solutions to the functions that require the lowest level of processing performance and progress towards the more processing-intensive functions.

The functions of presence detection and entrance/exit detection (FR1 and FR2) are the least demanding on the processing element. The applicable countermeasures corresponding to these functions are time-critical, but the real-time processing constraint is minimal, especially when compared with vehicle control. Advancements in electronic technology over the last decade have produced standard components with more than adequate throughput to support the countermeasures considered above. The only time constraint on the processor is that of notifying each driver of the presence of another vehicle, obstacle, or person in sufficient time to avoid a potential accident. This time constraint can be met by placing the sensor in an appropriate manner so as to supply the processor with data well in advance of an accident. The sensors chosen for these functions would typically produce a digital signal indicating the presence/absence of an object. The processor would then have to evaluate these sensor outputs and activate a warning device (i.e., audible alarm, light, roadside sign) if an object was present. This type of simple logical decision-making and switch activation can be implemented in programmable array logic (PAL) devices such as the Cypress 22V10. These devices have high-speed multiple I/O (up to twenty-two inputs and ten outputs with delays of tens of nanoseconds for the twenty-four-pin 22V10) and come in a variety of packages. With this amount of I/O, speed, and programmability, these devices would be able to handle multiple sensors and functions for under $15 per IC. It is obvious that for the functions of presence detection and entrance/exit detection that the processing requirements are not an issue.

Moving on to the next level of processing complexity, we shall consider the functional requirement of velocity measurement (FR4). The time constraints on the processor for the countermeasure functions associated with velocity measurement are similar to those of presence detection. Velocity measurements can be made by either making temporally different range measurements or evaluating the Doppler frequency from a radar sensor. Using the range measurement approach, the processor would be required to perform some simple arithmetical computations to extract velocity. For the Doppler frequency approach, the radar sensor would typically output an analog signal that was proportional to speed. This signal could be digitized and scaled by the processor to deduce velocity. Once the velocity is known, the processor would fuse this data with presence/absence data discussed above and an elementary algorithm to determine whether or not to activate a warning device. A device well suited for this type of processing application is an application-specific integrated circuit (ASIC). These devices allow for the mixture of analog and digital circuitry in one package. Therefore, an ASIC can include an analog-to-digital converter (A/D) to handle the Doppler frequency velocity measurements or a rudimentary arithemetic logic unit (ALU) to compute simple mathematical functions for temporal range difference velocity measurements. The ASIC could also handle logical decision-making similar to those discussed for the PAL processor above. ASIC manufacturers have become efficient in implementing specialized functions (i.e., A/D conversion) that has led to an increase in speed and throughput, and a reduction in cost and design turnaround times.

In regards to the other non-time-critical functions of driver condition monitoring and weather (road condition) monitoring (FR7 and FR8), the processing algorithms might be complex enough to use devices beyond PAL's and ASIC's. For example, to detect ice on the roadway, the processor may be required to fuse temperature, humidity, pressure, and precipitation data with different weighting factors in order to make an accurate assessment. Fuzzy-logic devices have been developed specifically for these types of problems. By categorizing inputs into so-called fuzzy sets and assigning membership functions, fuzzy-logic can accurately infer results for processes whose dynamics are not completely understood or accurately known. Fuzzy-logic was used by Nissan to control braking modulation for their antilock braking system. This type of application that requires monitoring a number of sensors and processing their feedback with varying emphasis illustrates fuzzy-logic performance and reliability. For the functions of driver-condition monitoring and weather (road condition) monitoring, fuzzy logic can be combined with other fundamental electronic circuitry (such as that discussed above) to make decisions on activating warning devices and performing arithmetical computations for advisory speed levels.

This brings us to the most taxing processing requirements of range and velocity monitoring (FR3 and FR5) for countermeasures like headway control and lateral steering. What makes these functions so demanding on the processing is their real-time processing requirements. Whenever one considers taking control of the vehicle away from the operator, the temporal management of the sensor data and control signals is crucial. For this reason, the processing for these functions should be handled by a microcontroller. Microcontrollers can be thought of as highly powerful specialized computer systems packaged on a single chip. Figure 59 depicts past and future trends for state-of-the-art microcontrollers. Today's 16-bit, single-chip microcontrollers (available from Intel, Motorola, and others) utilize a reduced instruction set computer (RISC) architecture and commonly have 250-ns instruction cycle times (i.e., 4 million instructions per second (MIPS)) with even higher speeds expected in the future. Microcontroller features include: choice of microprocessor, on-board RAM/ROM, 32 (or more) bi-directional I/O lines, 16-bit programmable timers, serial communication interfaces, multiple microprocessor interrupt lines, specialized arithmetic logic units (for high-speed computations), analog-to-digital and digital-to-analog converters, and intelligent peripheral devices (for graphic display controllers). Microcontrollers can even have on-board random logic for implementing some of the functions performed by the PAL's and ASIC's discussed above. It is likely that the flexibility and power of microcontrollers will lead to their application in countermeasures that include taking full or partial control of vehicle operations. In fact, other processing-intensive systems such as antilock brakes, traction control, suspension control, and airbag deployment make use of simple microcontrollers to supervise and regulate activities.

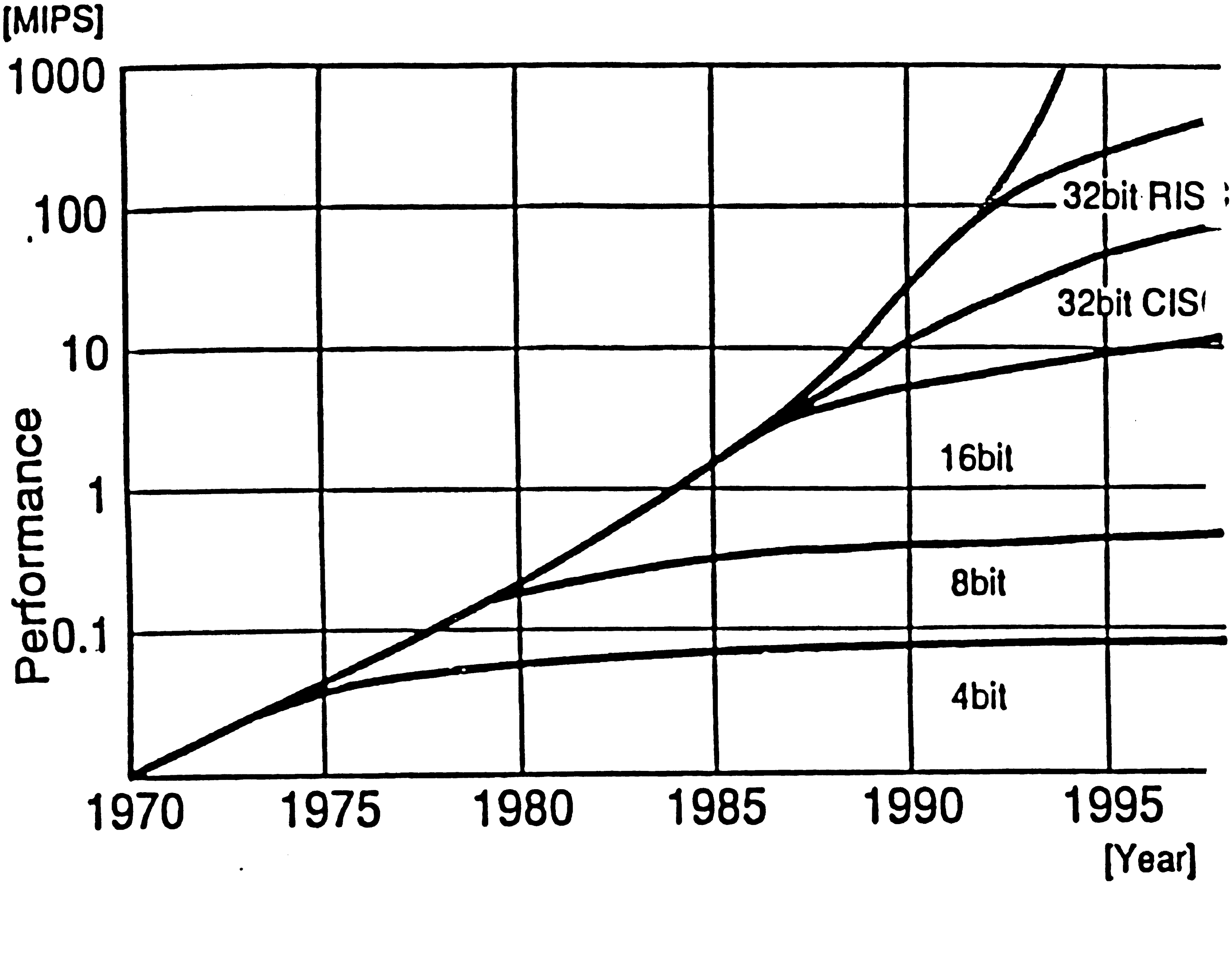


Figure 59. Microprocessor performance evolution.

In summary, the processing requirements for the countermeasures discussed in this report are manageable with the technologies provided by today's electronic technology and proper system engineering. The limiting constraint and criteria for technology choices is usually the time available for processing. Countermeasures that do not take control of the vehicle generally allow more time for the processing task and therefore can be implemented using a simpler technology. On the other hand, countermeasures that acquire some control of the vehicle operations must have information processed in a time-critical manner. These are more demanding on the processor and lead to a more complex technology implementation. However, as we have discussed in this section, electronic devices that are commercially available today have ample performance, input/output capacity, and reliability at a reasonable cost for the safety countermeasures discussed in this report. This fact is made evident by their successful employment in other automotive applications like anti-lock braking systems. (See references 25, 35, 51, 67, 70.)

Communications requirements and technology assessment

Along with the processing requirements just discussed, figure 58 also lists the fundamental communications requirements for the eight sensor technology functions. In general, communication systems for IVHS can be divided into four categories: intravehicle, vehicle-to-vehicle, vehicle-to-roadside, and roadside (i.e., roadside-to-traffic center or sensor-to-sign). Each of the four categories can be further divided into one-way and two-way systems. The reader should notice that the most difficult type of communications system from a technology standpoint—vehicle-to-vehicle—is not required to implement any of the countermeasures considered in this report. Further, the intravehicle data communication requirements can be fulfilled with simple guided channel systems, that are no different than existing vehicular electronic communications. The only drawback is the additional wiring harnesses; but with the advent of multiplex wiring systems, even this issue can be alleviated. Therefore, the remaining challenge for communications to support the active-safety technologies is to develop vehicle-to-roadside and roadside systems.

Theoretically, strict roadside communications could be handled by guided channel systems, however, the cost of installing and maintaining these systems is quite formidable. The other solution for roadside communications is to utilize a spectrum channel system. A spectrum channel system is also necessary for any vehicle-to-roadside communications. The issues associated with any spectrum communications system are throughput, bandwidth, power, and interference. In addition, high reliability, standard data formats (protocols), localization of transmission, and two-way communications at prevailing speeds are considerations for an IVHS communications system.

The most cost-effective way to achieve these desirable performance characteristics is through a radio frequency (RF) communications link.

The active-safety technology functional requirements that would utilize the RF links are presence detection (FR1), entrance/exit detection (FR2), range monitoring (FR3), velocity measurement (FR4), and weather monitoring (FR8). With the exception of range monitoring, the countermeasures associated with these functional requirements are not data-transfer intensive, and thus do not place unreasonable constraints on the throughput and bandwidth issues. With regards to range monitoring, the data transferred between the roadside and the vehicle would consist of upcoming road characteristics (i.e., turns) for automated steering corrections and lane-keeping. This information would not be transferred via a conventional communications system, but encoded in some cooperative infrastructure element, that would be deciphered by the sensor itself (i.e., radar). Therefore, this type of data communication will not be considered further in this section.

Returning to the functional requirements that do necessitate an RF link, a brief review of the associated countermeasures indicates that in all applications the data transferred via the communications system results in the activation of some warning device (e.g., a roadside sign or an in-vehicle indicator). Also, the information is specific to a localized area and one-way communications systems will suffice. Therefore, the resulting communications system for the safety countermeasures addressed in this report is a localized digital broadcast system (i.e., low power spread spectrum radio, SSR). Digital radio paging is a very mature technology and would provide more than sufficient performance for the applications under consideration.

In conclusion, it does not appear that the communication systems for the safety countermeasures considered in this report would pose any technological difficulties. Further, one should be aware that the intelligent vehicle/highway system community is addressing communication problems associated with much more demanding IVHS applications and that systems like the vehicle-to-roadside communications (VRC) link proposed by Hughes Aircraft in 1992 will be able to support multiple functions including safety countermeasures. IVHS AMERICA is currently considering standards and protocols for vehicle and roadside communications systems in order to provide compatibility of various vehicle products. It is this definition of standards and protocols and also the allocation of bandwidth from the Federal Communications Commission (FCC) that will allow the development of cost-effective communication systems for a variety of IVHS applications.[31,32]

Display requirements and technology assessment

From a technology standpoint, displays, both vehicle based and infrastructure based, do not pose any implementation impediments. Displays are abundant in a variety of sizes, shapes, and colors. Issues such as cost and aesthetics will be the major contributing factors toward choosing a display technology. Display technology for automotive applications has at its foundation considerable human factors issues. Display location, content, size, legibility, response time, resolution, color, and contrast ratio are all important considerations for selecting a display technology. The man-machine interface is of the utmost importance for ensuring the successful implementation of displays. This section will treat automotive display issues from both a vehicle-based and an infrastructure-based perspective. Many of the design considerations are common to both types of implementation.

Vehicle-based display

The design of vehicle-based displays involves many issues, such as display location, size, shape, luminescence, visibility, resolution, and cost. Cathode ray tube (CRT) displays have been developed to display travel information, route guidance directions, vehicle diagnostics, blind spot imagery, and night vision imagery. Research has been done involving electroluminescents (EL), plasma display (PDP), liquid crystal shutter (LCS/CRT), thin-film transistor/liquid crystal displays (TFT/LCD), and vacuum florescent display tubes (VFD).

Conventional automotive displays are embedded in the dashboard of the vehicle. Each time the driver requires speed, mileage, or status information, he is required to remove his glance from the scene and focus on the dashboard display. Such displays, for obvious reasons, are dubbed head-down displays (HDD). Head-up displays (HUD), on the other hand, allow the acquisition of the same information without requiring the driver to remove his glance from the roadway scene. HUD systems have been developed over the years and are now prevalent in military and civilian airplanes. In 1988, Nissan marketed the first automotive HUD. Also in 1988, General Motors introduced the HUD in its Oldsmobile Cutlass Supreme Indianapolis 500 pace car. The major advantage of HUD over HDD, as has been discovered through human factors research, is the short reacclamation or reaccomodation time associated with the HUD. Information generally available only by looking at the dashboard, is projected and superimposed on the driving scene requiring little adjustment in the driver's focal point.

Currently, only simple information (i.e., speed and status flags) is implemented in automotive HUD, however, roadmaps and imagery generated by night vision systems are proposed applications for future HUD research. Presently, image data is limited to head-down display implementations, for it is straightforward to route the output from a visible or infrared camera, or from a map data base directly into a conventional monitor.[19,58]

CHAPTER 6. FINDINGS REGARDING REDUCTIONS IN RISKS AND SEVERITY IN SELECTED CRASH TYPES

In this chapter the countermeasure systems described in chapter 4 are evaluated. The crosscutting countermeasures are evaluated first, then the crash-type-specific countermeasures are considered. Finally, each countermeasure is reviewed in terms of the following items:

- Problematic situations involved.
- Modes of driving involved.
- Information quantity, rate, and quality.
- Summary of the philosophical logic (rationale/justification).
- Assessment of the potential cost savings and effectiveness.

There are four basic conceptual steps in the analyses of crash situations. These steps involve identifying the crash type, reconstructing the crash situation as if it were to be replayed with the countermeasure in effect, calculating losses with and without the countermeasure, and assessing the cost reductions, that is, the benefits.

The methodology used in this study involves treating very many cases rather than extrapolating from detailed examinations of a relatively small number of hard copy cases.[74] Either approach may produce interesting results. In our predictions, we have made projections using the proportions of crash occurrences and severity levels derived from mass data pertaining to the current accident record. Nevertheless, the basic idea is to replay the accident data, going back to the original speed of travel if necessary, and then to determine the new outcomes that would occur if the countermeasure were in effect.

In the case of the crosscutting countermeasures, the crash situation is replayed using the crash data for each type of crash. For crash-type specific countermeasures, crash data for the specific type of crash is supplemented with analytical results pertaining to the influences of sensor range, driver response time, vehicle speed, and vehicle maneuvering (acceleration) capability in that type of crash. The results of replaying the crash situations are expressed in terms of the number of crashes in question, how many of those would be avoided, and how many would have resulted in property damage or slight injury, serious injury, or fatality.

In addition to using the results of physical analyses for estimates of countermeasure efficiency, a generic effectiveness estimation method was developed. It involved identifying the number of cases upon which the countermeasure might have an effect and assuming that a portion of these cases would still result in a crash, even with the countermeasure. This portion was estimated as the ratio of the crashes upon which the countermeasure definitely has no effect on the total number of crashes. The derivation of this estimation technique can be found in Appendix A. As in the analytic methods, the result is given in the number of crashes avoided, the number resulting in property damage or slight serious injury, injury, or fatality.

Perhaps a hypothetical numerical example will aid in clarifying the ideas involved in assessing the crash avoidance benefits. Figure 60 shows before and after results for a simplified example. The figure illustrates the results predicted for a countermeasure system applied in the context of a particular crash type. Before the countermeasure was applied, the crash situation involved 1200 property damage (or slight injury) crashes (PD,s), 1000 injury crashes (INJ's), and 100 fatals (FAT's). (Round numbers have been picked to keep the arithmetic simple.) The countermeasure has the effect of eliminating some of the crashes altogether and reducing the severity of some of the crashes. In this example, the FAT's were reduced to 80, the INJ's were reduced to 800, and the PD's were reduced to 800. This means that 620 crashes were prevented altogether. (Later we will discuss details of how these predictions are obtained.) The point here is to provide a set of changes in crash data for use in illustrating how relative costs have been determined in this project.

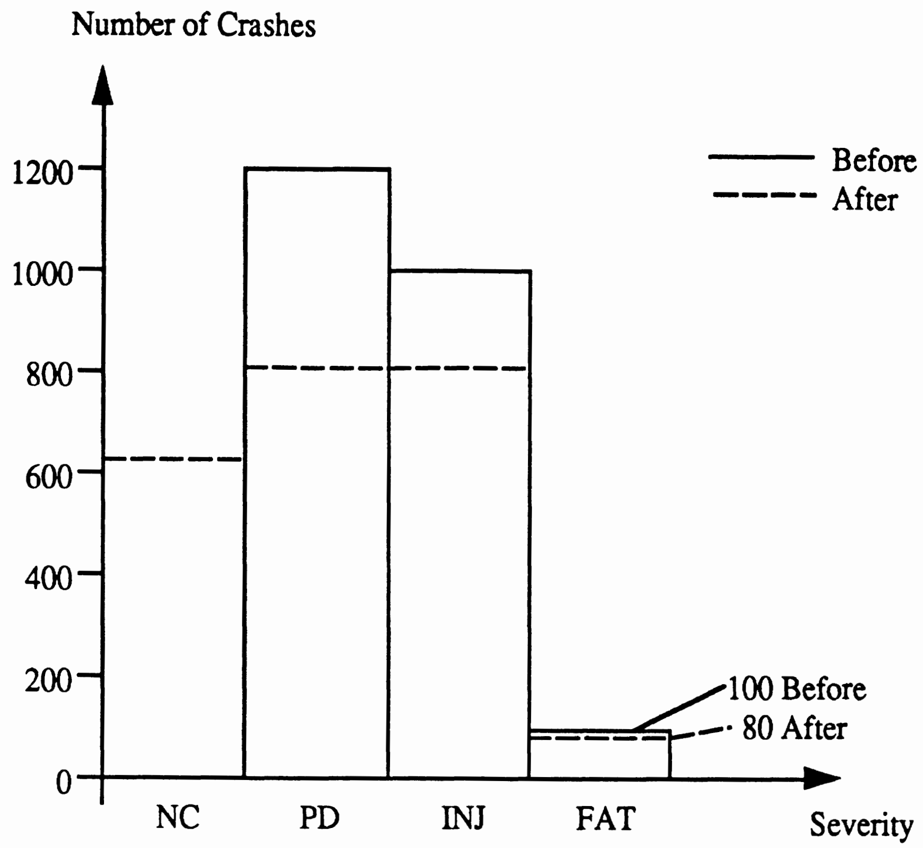
The costs for PD's to INJ's to FAT's are estimated to be approximately 1 to 10 to 200 in terms of relative cost factors (to keep the arithmetic simple). The savings in crash properties pertaining to the hypothetical example, shown in figure 60, would correspond to those associated with 20 FAT's, 200 INJ's, and 400 PD's. Using the relative cost factors, table 25 shows the "before countermeasure" costs, the "after countermeasure" costs, and the cost savings:

Table 25. Relative costs and savings [**costs** (number)].

	BEFORE	AFTER	SAVINGS
PD	**$1,200** (1200)	**$800** (800)	**$400** (400)
INJ	**$10,000** (1000)	**$8,000** (800)	**$2,000** (200)
FAT	**$20,000** (100)	**$16,000** (80)	**$4,000** (20)
TOTALS	**$31,200**	**$24,800**	**$6,400**

The ratio of cost savings to the total cost before the countermeasure is a generalized measure of the crash benefit of the countermeasure. In this case the result is \$6,400/\$31,200 or approximately 0.21 (21 percent). This is interpreted to mean that the hypothetical countermeasure is predicted to provide a 21 percent reduction in crash costs. (The example represents a very successful countermeasure. Nevertheless, it illustrates the basic ideas used in evaluating the influence of a countermeasure in a particular type of crash.)

The example also provides a quantitative feel for the importance of fatal crashes. The savings from 20 FAT's were more beneficial that the savings from 200 INJ's or 400 PD's because each FAT is equivalent in cost to approximately 20 INJ cases or 200 PD cases. This means that special attention needs to be applied to fatal crashes in order to make rational predictions.



NC -- No crash

PD -- Property damage (and/or minor injury)

INJ -- Injury

FAT -- Fatal

Figure 60. Hypothetical example of crashes before and after a countermeasure.

The relative costs used in the previous example were simplified relative to the costing scheme used in the analyses of the countermeasure systems. The costs of the accidents used in this work are derived from comprehensive costs of highway crashes developed by Miller et. al in 1991 for the Federal Highway Administration [75]. Miller et al. present comprehensive crash costs per crash and per person for five levels of severity: fatal, incapacitating injury (A), evident injury (B), possible injury (C), and property damage only (PDO) and do not differentiate these costs by crash type. However, in this research three levels of crash severity: fatal, injury, and property damage and/or minor injury, were used and the costs for each of these three severity categories for six crash types were needed. These were developed as follows:

The costs of fatal accidents were obtained by using the costs per injury from reference 75 and the average number of fatalities, A, B, and C injuries in fatal accidents for each crash type in the 5-percent CARDfile sample of crashes used to develop the crash typology earlier in this research. The cost of an injury crash for each of the six crash types was obtained similarly by using the average number of A, B, and C injuries for each crash type, classified as crash severity A or B in the 5-percent CARDfile and multiplying these numbers by the appropriate cost per injury.

The costs of the third severity category, PDO or minor injury, were obtained by taking the costs for C injury crashes and for PDO crashes for each crash type and using the proportions of injury C and PDO crashes for the crash type to get the cost for that category.

The average costs of injury C accidents were obtained from the average number of C injuries for the C category crashes of each type in the 5-percent CARDfile sample and the comprehensive cost of a C injury reported by Miller. The PDO costs were obtained by using the overall average cost of a PDO crash reported by Miller, the distribution of the number of vehicles involved in the crashes in the 5-percent CARDfile sample, and the assumption that the cost of a "n" vehicle accident, where n is the number of vehicles involved, would be n times that of a single vehicle accident.

Table 26 shows the average number of injuries by crash type for each of the three levels of severity in the 5-percent CARDfile sample and the proportion of C injury and PDO crashes in the least severe category of crashes.

Table 26. Average number of fatalities and injuries per accident.

Fatal Accidents		Average Number of Injuries		
Accident Type	Ave. No. of Fatalities	A	B	C
Run-Off-the-Road	1.08	.25	.38	.10
Ped/Bike/Animal	1.00	.04	.01	.03
Crossing Paths	1.08	.63	.59	.26
Left Turn	1.08.	.55	.65	.25
Rear-End	1.03	.17	.31	.36
Head-On	1.22	.64	.98	.30
All Others	1.12	.35	.30	.19

A & B Injury Accidents	Average Number of Injuries		
Accident Type	A	B	C
Run-Off-The-Road	.94	.13	.11
Ped/Bike/Animal	.38	.64	.01
Crossing Paths	1.14	.32	.45
Left Turn	1.11	.33	.41
Rear-End	1.01	.27	.38
Head-On	1.16	.51	.42
All Others	.98	.33	.31

PDO/C Injury Accidents	Average Number of		Proportion of Crashes	
Accident Type	Inj C	Vehicles	C Inj	PDO
Run-Off-The-Road	1.18	1	.22	.78
Ped/Bike/Animal	1.01	1	.20	.80
Crossing Paths	1.39	2	.24	.76
Left Turn	1.44	2	.27	.73
Rear-End	1.35	2	.26	.74
Head-On	1.47	2	.25	.75
All Others	1.39	1.8	.16	.84

The following comprehensive costs from reference 75 were used: \$2,392,742 per fatal injury, \$169,506 per an A injury, \$33,227 per a B injury, \$17,029 per a C injury and \$4,489 for a property damage only crash. Note, costs of property damage that occurred in a fatal or injury crash are accounted for in the per injury cost.

Table 27 shows the resulting accident costs by severity for each accident type used in this analysis.

Table 27. Accident cost by type and severity.

Accident Type	PDO/Inj C	Injury A, B	Fatal
Run-Off The-Road	6,338	171,509	2,640,867
Pedestrian/Cyclist/Animal	5,406	85,848	2,400,365
Crossing Paths	9,417	211,533	2,714,982
Left Turn	10,210	206,098	2,703,244
Rear-End	9,615	186,643	2,509,771
Head-On	9,945	220,725	3,065,300
All Others	7,558	182,360	2,752,402

ESTIMATION OF BENEFITS FOR THE CROSS CUTTING COUNTERMEASURES

Method

The random 5-percent sample of police-reported accidents from the NHTSA CARDfile originally used in this research to develop a collision typology was used in the evaluation of the potential safety benefits of the countermeasures. For each collision type, the subset of crashes, defined by associated factors that the countermeasure was designed to address, was identified. It was assumed that if the countermeasure had been in effect, some of these crashes would not have occurred and the severity of those that did occur would be different from that originally observed. It was also assumed that the collisions, in the categories not addressed by a particular countermeasure, would occur exactly as they did before.

For each subset of crashes affected by the countermeasure, it was assumed that the number of accidents that would not have occurred would be proportional to the portion of accidents in the subset affected by the countermeasure. For example, since 25.7 percent of all run-off-the-road collisions in the accident data file are associated with alcohol, it is assumed that if the driver impairment countermeasure was in place everywhere, 74.3 percent of the run-off-the-road collisions, originally not associated with alcohol, would still occur.

It was further assumed that the severity of the accidents that still occurred would be distributed as observed in the original subset of accidents, defined by all the same associated factors, except the one addressed by the countermeasure. For example, take a set of accidents with the associated factors of darkness, low friction, and alcohol. If an impaired driver countermeasure had been in place we assume that the severity of those collisions that still occurred would be distributed like the crashes with the associated factors of darkness and low friction only.

The number of crashes by severity, as found in the CARDfile sample, was compared to that determined by the procedure described above for each crash type for each of the three cross cutting countermeasures, i.e., driver impairment countermeasure, vision enhancement, and the low friction countermeasure. A monetary cost of the accidents for the crashes with and without the countermeasures was also compared. Table 28 shows the number of accidents in the CARDfile sample used in this benefit analysis by crash type and severity and monetary cost.

Table 28. CARDfile sample of accidents used in countermeasure evaluations.

			Severity			
Crash Type	Total No.	PDO/Inj C	Injury A & B	Fatals	Total Cost*	% of Cost
Run-off-the-road	31,709	22,814	8,548	347	$2,527,034,913	22.01%
Pedestrian/cyclist/animal	11,112	7,861	3,076	175	726,628,889	6.33%
Crossing paths	22,473	18,191	4,183	99	1,324,930,404	11.54%
Left turn	11,317	8,825	2,452	40	703,585,306	6.13%
Rear-end	38,800	34,729	4,035	36	1,177,375,596	10.25%
Head-on	7,047	4,994	1,858	195	1,057,505,880	9.21%
Total of above	122,458	97,414	24,152	892	$7,517,060,988	65.47%
All others	89,416	76,319	12,708	389	3,964,934,260	34.53%
Total in sample	211,874	173,733	36,860	1,281	$11,481,995,248	100.00%

* Accident cost by crash type and severity

Crash Type	PDO/Inj C	Injury A & B	Fatals
Run-off-the-road	6,338	171,509	2,640,867
Pedestrian/cyclist/animal	5,406	85,848	2,400,365
Crossing paths	9,417	211,533	2,714,982
Left turn	10,210	206,098	2,703,244
Rear-end	9,615	186,643	2,509,771
Head-on	9,945	220,725	3,065,300
All others	7,558	182,360	2,752,402

Impaired Driver Countermeasure (CM2 in table 1 in chapter 4)

The impaired driver countermeasure addresses all six collision types and is therefore a cross-cutting countermeasure. At this point, it was assumed that the countermeasure makes the impaired driver behave as an unimpaired driver. Table 29 summarizes the results of the benefit calculation for the impaired driver countermeasure. Appendix B shows the details in determining the changes in the number and severity of accidents for the alcohol related accidents for all six collision types.

Vision Enhancement Countermeasure (CM1 in table 2 in chapter 4)

The vision enhancement countermeasure is also a cross cutting countermeasure. In the benefit estimation it is assumed that the effect of this countermeasure is to bring all the situations resulting in accidents in the CARDfile sample to daylight conditions. Table 30 summarizes the results of the benefit calculation for the vision enhancement countermeasure. Appendix C shows the details of determining the changes in the number and severity of darkness-related accidents for all six collision types.

Low-Friction Countermeasure (CM3 and 4 in table 1 in chapter 4)

The low-friction countermeasure is assumed to work by warning the motorists of low-friction conditions and informing them of the safe speed for the conditions. It is assumed that unimpaired drivers heed the warning and adjust their speed accordingly. It is also assumed that impaired drivers do not heed the warning, and that this countermeasure has no effect on any alcohol-related incident. Therefore, the accidents used for benefit calculations for this countermeasure are only those that occurred in low friction conditions and were not associated with alcohol.

Since, the effect of countermeasure is to get drivers traveling at speeds excessive for the conditions to reduce their speed, the distribution of the severity of accidents that occur even after the countermeasure is in place is assumed to be that of accidents associated with low-friction and speed not excessive for the conditions.

Table 31 shows the results of the benefit calculations for the low-friction countermeasure. Appendix D shows the details of the calculations for each collision type for this countermeasure.

Table 29. Reductions in accidents and cost from impaired driver countermeasure (by crash type).

Crash Type	Total No.	PDO/Inj C	Injury A & B	Fatals	Total Cost
Run-off-the-road	2,100	301	1,661	138	$651,223,833
% change	6.62%	1.32%	19.43%	39.77%	25.77%
Pedestrian/cyclist/animal	17	(71)	65	23	60,404,689
% change	.15%	-.90%	2.11%	13.14%	8.13%
Crossing paths	64	(141)	187	18	87,098,550
% change	.28%	-.78%	4.47%	18.18%	6.57%
Left turn	36	(78)	106	8	42,675,960
% change	.32%	-.88%	4.37%	20.00%	6.07%
Rear-end	174	(216)	379	11	96,268,338
% change	.45%	-.62%	9.39%	30.56%	8.18%
Head-on	162	(103)	217	48	194,007,390
% change	2.30%	-2.06%	11.68%	24.62%	18.35%
Total reduction	2,553	(308)	2,615	246	$1,131,678,760
% change	2.08%	-.32%	10.83%	27.58%	15.05%

( ) Indicates an increase.

Table 30. Reductions in accidents and cost from enhanced vision countermeasure (by crash type).

Crash Type	Total No.	PDO/Inj C	Injury A & B	Fatals	Total Cost*
Run-off-the-road	4,713	3,241	1,361	111	$547,101,444
% change	14.86%	14.21%	15.92%	31.99%	21.65%
Pedestrian/cyclist/animal	1,988	2,698	(722)	12	(18,592,488)
% change	17.89%	34.32%	-23.47%	6.86%	-2.56%
Crossing paths	115	21	75	19	67,647,390
% change	.51%	.12%	1.79%	19.19%	5.11%
Left turn	77	43	30	4	17,434,946
% change	.68%	.49%	1.22%	10.00%	2.48%
Rear-end	425	210	204	11	67,701,803
% change	1.10%	.60%	5.06%	30.56%	5.75%
Head-on	255	133	77	45	156,257,010
% change	3.62%	2.66%	4.14%	23.08%	14.78%
Total reduction	7,573	6,346	1,025	202	$837,550,105
% change	6.18%	6.51%	4.24%	22.65%	11.14%

( ) Indicates an increase.

Table 31. Reductions in accidents and cost from low- friction countermeasure (by crash type).

Crash type	Total No.	PDO/Inj C	Injury A & B	Fatals	Total Cost
Run-off the-road	4,357	3,487	855	15	$208,353,806
% change	13.74%	15.28%	10.00%	4.32%	8.24%
Pedestrian/cyclist/animal	38	25	12	1	3,565,691
% change	.34%	.32%	.39%	.57%	.49%
Crossing paths	296	244	51	1	15,800,913
% change	1.32%	1.34%	1.22%	1.01%	1.19%
Left turn	79	66	13	0	3,353,134
% change	.70%	.75%	.53%	.00%	.48%
Rear-end	2,764	2,471	293	0	78,445,064
% change	7.12%	7.12%	7.26%	.00%	6.66%
Head-on	988	853	126	9	63,882,135
% change	14.02%	17.08%	6.78%	4.62%	6.04%
Total reduction	8,522	7,146	1,350	26	$373,400,743
% change	6.96%	7.34%	5.59%	2.91%	4.97%

( ) Indicates an increase.

Summary and evaluation of benefit results for cross cutting CMS

Table 32 summarizes the benefits of the cross cutting countermeasures. It should be noted that it was assumed that the countermeasures were universally applied and were totally effective. Therefore, the quantification of benefits presented here is basically an estimate of the upper limits of the potential benefits of the countermeasures.

Further refinements of the estimates of the potential benefits of the cross cutting countermeasures depend upon having a means for predicting the effectiveness of countermeasure systems based upon specific details of the system and results of analyses, simulations, and experiments. The results here are for an effectiveness of 1.0 and depending upon the reliability, capability, acceptance, useability, etc. of the countermeasure system, the effectiveness might be considerably less than 1.0.

Table 32. Benefit summary of cross cutting countermeasures.

Using only the 6 crash types

	Reductions in accidents by severity				Cost
	Total No.	PDO/Inj C	Injury A & B	Fatals	Reduction
Impaired driver CM	2.08%	-.32%	10.83%	27.58%	15.05%
Enhanced vision CM	6.18%	6.51%	4.24%	22.65%	11.14%
Low-friction CM	6.96%	7.34%	5.59%	2.91%	4.97%

Using the entire CARDfile subset

	Reductions in accidents by severity				Cost
	Total No.	PDO/Inj C	Injury A & B	Fatals	Reduction
Impaired driver CM	1.20%	-.18%	7.09%	19.20%	9.86%
Enhanced vision CM	3.57%	3.65%	2.78%	15.77%	7.29%
Low-friction CM	.02%	4.11%	3.66%	2.03%	3.25%

ESTIMATION OF BENEFITS FOR CRASH-TYPE SPECIFIC COUNTERMEASURES

Methods

To provide background for the crash analyses that follow, this subsection summarizes relationships between distance, time, speed, and acceleration pertaining to the crash types and their countermeasure systems.

The basic premise of the estimating method is that if the situational demands for crash avoidance action exceed the available crash avoidance capabilities, there is a crash. Countermeasures are beneficial when crash prevention provisions and crash avoidance capabilities are enhanced to the point where crashes are either eliminated or their severity is reduced.

Braking—In braking situations, crash avoidance provisions and capabilities are measured by the following factors:

D - Range at which hazards are recognizable.

T - Reaction time between observation and control action.

V - Traveling speed when the hazard was recognized.

A - Acceleration (deceleration) available to be used.

Nominally, in a balanced situation,

$$D = TV + V^2/2\,A \tag{7}$$

However, there can be mismatches during a trip. For example, let the "actual" values of D, T, V, and A be symbolized by Da, Ta, Va, and Aa, respectively, and consider the following unfavorable situations:

- $Da < (TV + V^2/2\,A) = D$

In this case Da could be much shorter than D because the driver is unaware of or inattentive to a hazard ahead or the driver's vision is obscured.

- $Ta > T$

In this case Ta may be longer than it needs to be because the driver is impaired or the driver's level of expectation of a problematic situation is low.

• $Va > V$
In this case Va may be higher than the situation warrants because of poor judgment or unawareness of hazardous situations.

• $Aa < A$
In this case Aa may be less than that expected because the road is slippery or the vehicle's hardware is defective.

In these cases D, T, V, and A are not coordinated. The equation (7) does not hold in a manner such that the above items represent unfavorable, risky situations.

However there can be favorable situations, as illustrated in the following examples:

• Long sight distance.
$Da > (TV + V^2/2A) = D$
(This is like the stopping sight distance concept as applied to crest vertical curve design.)

• Short response time.
Ta is shorter than the T used in equation (7).

• Moderate speed.
Va is lower than the V used in equation (7).

• High deceleration capability.
Aa is larger than the A used in equation (7).

The countermeasures have the goal of changing unfavorable situations into favorable situations.

Crash severity depends upon the velocity at the crash, Vc. When a crash occurs,

$$(Vc)^2 = V^2 - 2A(Dc - TV) \tag{8}$$

where Dc = the distance to where the crash occurs.

If (Dc - TV) is negative, the crash occurs before the driver (or a control intervention countermeasure) has had time to react, and $Vc = V$. If the above equation (8) indicates that $(Vc)^2$ is negative under the influence of a countermeasure, the vehicle stops before crashing, $Vc = 0$.

Equation (8) has been used as a means for assessing the effectiveness of various countermeasures with various levels of capability as might be influenced by the state of technology or the desire for eliminating false alarms. In order to do this it is necessary to pick values of Dc (from now on symbolized as D to simplify the notation used) (T, V, and A). In a generic sense, D represents the range of the countermeasure system, T represents the alertness of the driver (or the state of impairment), V represents the speed of travel, and A represents the frictional capability of the tire/road interface. To represent any given situation, values of D, T, V, and A have been selected depending upon the nature of the situation that we are trying to represent and the features of the countermeasure involved.

Following the ideas described in the paragraph above, table 33 illustrates a set of choices and results in terms of Vc and deltaV for different values of Vt (the traveling speed) for a countermeasure with a maximum range of 300 ft. Column A contains a range of traveling speeds running from 5 to 75 mi/h. The computations run horizontally across the table for each speed. Column C presents results that are close to those that are used in the design of crest vertical curves. In this case they are based on T = 2 sc and A = 0.3 g as a fair approximation to the highway design criteria. (These represent values for about a 99-C percentile worst driver and a poor wet road.) In the interest of eliminating false alarms at low speeds, these values are used in column D up to the point where they become greater than 300 ft, which is the maximum range at which hazards can be identified by the countermeasure. Column E is set at 1 s to represent an alerted driver. This value is slightly higher than average for alerted drivers (see figure 13 on page 44 of ref. 6.3). Column F is set at 16 ft/s^2 to represent a deceleration capability of 0.5 g. This represents a drastic stop corresponding to a situation in which the road and the vehicle are in good condition. The remaining columns up to columns K, L, and M contain the results of intermediate calculations. The results, presented in columns L and M, indicate that there would be no crashes for initial traveling speeds up to 55 mi/h and that the deltaV values at 65 and 75 mi/h would be approximately 21 and 32 mi/h respectively. This example illustrates the manner in which the application of braking has been replayed for various situations pertinent to the evaluation of safety benefits.

Steering or steering and then braking—In problematic situations involving directional control, such as run-off-the road situations, there is a need to estimate whether a steering correction would be sufficient to correct the problem.

Table 33. Example calculations for a braking case.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	vel.Vo mph	Vo ft/sec	Dsr ft.	D 300 max	T	A	D -Vo T	2A(D-Vo T)	Vo**2	Vs**2	Vs ft/sec	Vs mph	Delta V mph
2	5	7.3335	17.4	17.4	1	16	10.0665	322.128	53.78022225	-268.3477778	0	0	0.00
3	15	22.0005	69.2	69.2	1	16	47.1995	1510.384	484.0220003	-1026.362	0	0	0.00
4	25	36.6675	143.3	143.3	1	16	106.6325	3412.24	1344.505556	-2067.734444	0	0	0.00
5	35	51.3345	240	240	1	16	188.6655	6037.296	2635.23089	-3402.06511	0	0	0.00
6	45	66.0015	359	300	1	16	233.9985	7487.952	4356.198002	-3131.753998	0	0	0.00
7	55	80.6685	500	300	1	16	219.3315	7018.608	6507.406892	-511.2011078	0	0	0.00
8	65	95.3355	663	300	1	16	204.6645	6549.264	9088.85756	2539.59356	50.39438024	34.35902383	20.62
9	75	110.0025	850	300	1	16	189.9975	6079.92	12100.55001	6020.630006	77.59271877	52.9029241	31.74

In steering situations, crash avoidance provisions and capabilities depend upon the following factors in these analyses:

Aymax - Maximum lateral acceleration used in a steering correction.

Ts - Period of the steering action.

V - Traveling speed when the hazard was recognized.

T - Driver and countermeasure response time combined.

Alpha - Angle at which the vehicle is leaving the road or its lane.

Yobs - Lateral distance to an obstacle (for vehicles in crashes).

Aoff - Deceleration capability when brakes are applied off the road.

The equation used for the lateral distance (Ymm) achieved by the steering correction is as follows:

$$\text{Ymm} = \text{Aymax}\ (\text{Ts})^2 / 6.28 \qquad (9)$$

This equation is based on a lateral acceleration of the form:

$$\text{Aymax}\ \sin(6.28\ t / \text{Ts})\ \text{for}\ 0<t<\text{Ts}$$

Ymm is the lateral displacement at the end of the maneuver when t = Ts. The idea is to move the vehicle laterally without using too large of an acceleration (Aymax) and without using too much time (Ts).

During this period, the vehicle moves laterally with respect to the road edge depending upon the speed of travel (V), the angle of road departure (alpha), and the time period (Ts). To figure out where the vehicle is with respect to the road edge at the end of the maneuver, the following auxiliary variable is introduced:

$$\text{Yveh} = \text{V}\ (\text{Alpha})\ \text{Ts} \qquad (10)$$

The difference (Ymm - Yveh) represents the location of the vehicle with respect to the road edge at the end of the steering correction.

Countermeasures 5 and 6 for run off road situations could involve braking if the steering correction and subsequent driver actions did not keep the vehicle under control. The idea would be to apply the brakes if the vehicle were off the road after the steering correction ended. If it is assumed that steering feel and accompanying audio warnings got the drivers attention by the time the steering correction was over, the driver's response time or the countermeasure's response time could be nearly over. This means that the brakes would be applied close to a point with a lateral coordinate of (Ymm - Yveh).

The angle of departure (Alpha) has a major influence on the distance traveled before striking something or rolling over off the road. For a straight road section, the angle of departure might be quite small. For example, Alpha = 0.01 radians (0.5 degrees) is a possibility. Furthermore, if the lateral distance to an obstacle is 10 ft and Alpha = 0.01 radians (0.5 degrees) then the available braking distance is 1000 ft. In contrast, if Alpha is 0.05 radians (3 degrees), the available braking distance is 200 ft. The 3-degree angle of departure is like that corresponding to the start of a 3-degree curve in highway parlance. (This means a curve with a radius of approximately 1900 ft., which is small, but not unusual for a curve on an interstate quality road.)

However, it may be that accidents occur in situations where the angle of departure is larger than those given above. We have no information to use for setting the value of Alpha to use in our design evaluation analyses. Nevertheless, to perform evaluations, our design evaluation cases are as follows:

Alpha = 0.02 radians for straightaways

Alpha = 0.06 radians for curves

To illustrate the ideas discussed above, consider the example given in table 34.

The input data describing a run-off-road situation is given in the upper third of the table. The middle third (rows 11 through 19), has to do with whether the vehicle would have run off the road after a steering correction, which peaks at Ay=4 ft/s^2, and if so, what is the available stopping distance. Column F indicates whether the vehicle would run-off-the road and column E indicates the distance to a crash with an obstacle that is offset 10 ft from the road edge.

The bottom third of the table (rows 21 through 29) cover the results of a braking analysis corresponding to the run off road situation. This section of the table is similar to table 33, pertaining to braking situations. However, in this case, the entries in the braking

Table 34. Example run-off-road calculation.

	A	B	C	D	E	F	G	H	I	J	K
1	spread sheet for lateral /steering CMs										
2	Aymax	ft/sec/sec	4		Y CM (ft)	2.547770701					
3	T steer period	sec	2		Doff (ft)	500					
4											
5	T driver or CM	sec	0.1								
6	alpha	radians	0.02								
7	Y obs	ft	10								
8	A off road	ft/sec/sec	8								
9											
10											
11	vel.Vo mph	Vo ft/sec	Y vehicle	Y CM - Y veh	D	0 = no ROR					
12	5	7.3335	0.29334	2.254430701	612.721535	0					
13	15	22.0005	0.88002	1.667750701	583.387535	0					
14	25	36.6675	1.4667	1.081070701	554.053535	0					
15	35	51.3345	2.05338	0.494390701	524.719535	0					
16	45	66.0015	2.64006	-0.092289299	495.385535	1					
17	55	80.6685	3.22674	-0.678969299	466.051535	1					
18	65	95.3355	3.81342	-1.265649299	436.717535	1					
19	75	110.0025	4.4001	-1.852329299	407.383535	1					
20											
21	vel.Vo mph	Vo ft/sec	D	D -Vo T	2A(D-Vo T)	Vo**2	Vs**2	Vs**2 ft/sec	Vs	Vs mph	Delta V mph
22	5	7.3335	612.721535	611.988185	9791.810961	53.78022225	-9738.030738	0	0	0	0.00
23	15	22.0005	583.387535	581.187485	9298.999761	484.0220003	-8814.97776	0	0	0	0.00
24	25	36.6675	554.053535	550.386785	8806.188561	1344.505556	-7461.683004	0	0	0	0.00
25	35	51.3345	524.719535	519.586085	8313.377361	2635.23089	-5678.14647	0	0	0	0.00
26	45	66.0015	495.385535	488.785385	7820.566161	4356.198002	-3464.368158	-3464.368158	0	0	0.00
27	55	80.6685	466.051535	457.984685	7327.754961	6507.406892	-820.3480683	-820.3480683	0	0	0.00
28	65	95.3355	436.717535	427.183985	6834.943761	9088.85756	2253.9138	2253.9138	47.47540205	32.36885665	19.42
29	75	110.0025	407.383535	396.383285	6342.132561	12100.55001	5758.417446	5758.417446	75.88423714	51.73807673	31.04

analysis for distance depend upon the results given in column E, rows 12 through 19, and the appropriate input data given in the upper third of the table.

In this example, Alpha equals 0.02 radians, representing a straight road section. Other design evaluation examples (as used in this study) are given in appendix E .

In case of countermeasure 7, involving speed warnings for slippery curves, the super-elevation of the roadway has a large bearing upon the speed at which the curve can be negotiated. Highway curves are designed very conservatively (as they should be) which means that very little shear force from the tires is required to negotiate curves (something like a friction of about 0.14 is used for modest design speeds and even lower friction is used for high design speed roads). In addition, the super-elevation policy used in designing curves uses a substantial amount of super-elevation such that tire/road friction does not play a large part in getting vehicles around curves that are not as sharp as the sharpest curves on the road.[7] This all means that roads are built so that vehicles can get around curves at fairly high speeds as long as they do not have to maneuver to resolve a conflict. The primary question is: How much of the available friction should be saved for use in resolving conflicts? A possible answer, for example, is to save at least 1/2 the available friction for resolving conflicts.

In super-elevated curves, the equation for lateral acceleration/force balance is as follows:

$$(V^2 / Rg) - e = mu \tag{11}$$

where V is velocity, R is radius of the curve, g is the acceleration of gravity, e is the super-elevation, and mu is the side friction used in negotiating the curve. In highway design, V, R, e, and mu are coordinated depending upon the design speed of the road and the super-elevation policy for the road.[7] What we do here is to consider a curve site with known R, e, and friction factor f. If the current mu is less than 2f, we use equation 11 to solve for V using a friction level of 0.5 mu. In equation form:

$$V = sqrt\{(0.5\ mu + e)\ g\ R\} \tag{12}$$

where sqrt{ } represents the square root function. For example, if AASHTO policy is followed and the design speed of the road is 40 mi/h and e maximum = 0.1, R = 573 ft, and e = 0.094.[7] In this case, the recommended speed using equation 12 would be 35 mi/h. If we had let super-elevation alone do the job (that is, if no friction were used in following the curve), the recommended speed would still have been 29 mi/h.

Perhaps a conservative rule would be to have the speed determined by a "friction commitment," $fc = (mu - f) / 2$ for $2f > mu > f$ and $fc = 0$ for $mu < f$. If $2f \leq mu$, there would be no special warning for low friction.

Head-on situations—In potential head-on crash situations there is difficulty in deciding what to do to avoid the crash. Should one steer or brake or both? In analyzing this situation, we have used the lateral displacement equation 9:

$$Ymm = Aymax\,(Ts)^2 / 6.28$$

with Ymm = 6 ft and Aymax = 0.3 g, that is, 9.6 ft/sec/sec. In this case, we solve for Ts and then use $Ts \cdot V$ to compute the maneuvering component of the headway distance. The total headway distance needed includes an additive term equal to the driver's response time (T), which should be short if the driver is alerted. Given the above description, Ts = 2.0 s and T is approximately 1 s. This means that the headway distance (Dh) needed at velocity V is given as follows:

$$Dh = (Ts + T) \cdot V = 3V \qquad (13)$$

Equation (13) is used in connection with curved road sections to assess the capability of countermeasures that provide early warnings of vehicles that are obstructed from view around curves. On straight sections of road without vision obstructions there is usually plenty of sight distance. However, a warning of someone approaching in their passing lane and your traveling lane might be appreciated if it came in time for you to do something that was not too drastic.

Perhaps the best means to prevent head-ons is to provide a means for keeping vehicles in their lane. In that case, a path-following analysis applies.

All of the head-on countermeasures might be candidates for spot improvements rather than universal improvements. Their tradeoff between effectiveness and cost is likely to be such that selecting appropriate sites for applying these countermeasures is important in getting a reasonable chance for payoff in terms of reductions in crash costs. The trick is to be able to pick sites where head-on crashes are likely to occur.

Intersections—Intersection situations are difficult to analyze unless there is a powerful concept to use in preventing crashes. Stop signs and traffic lights represent the implementation of two types of powerful concepts. Overpasses (and flyovers) represent another powerful concept in which crossing traffic streams are simply separated by vertical space.

The concept of the four-way stop is to stop all drivers and then to let individual drivers take turns using the intersection space for traveling to where each individual wants to go. This approach can cause traffic delays but it is an effective safety countermeasure if flow is not too large. A traffic signal increases the flow by letting two directions go at once. Drivers wanting to turn left need to find gaps except in the case of signals that have protected left-turn phases. The point is that changing intersection rules will have a large influence on traffic flow. Hence, the operational influences of safety applications at intersections need to be considered.

For example, the introduction of two four-way stops into the downtown region of a small city has been simulated. The results showed that this change would put the whole downtown area into gridlock during peak travel periods. However, the use of two-way stops at these intersections worked out well. There was no gridlock and the drivers on the stopped directions could find gaps to use in getting to where they wanted to go without having to wait too long. Nevertheless, drivers trying to make left turns after stopping at a two-way stop have much information to consider. They need to look to both sides as well as straight ahead. They need to predict where they would be if they were to enter the intersection and where the other vehicles would be also. Depending upon the traffic situation, there can be an information processing delay such that it may be difficult and it may take a long time for drivers to perform the turn (depending upon the driver's motivation to hurry).

The countermeasures offered here deal with stops at intersections of minor roads with major roads and a means for countering the possibilities of people running stop signs or pulling out into the intersection when another vehicle is already there. The ideal four-way stop would not have these problems, but the common types of mistakes leading to crashes are either: (1) running the stop sign or (2) stopping and then pulling out into the path of another vehicle. The countermeasures were designed using braking, steering, and sight distance factors along with vehicle presence detectors to provide warnings to aid drivers in finding appropriate gaps in the traffic flow.

The following material documents result from the benefits (crash reduction) analyses that have been performed:

Countermeasures involving braking (CM's 8, 9, 10 and 11)

The basic quantities used in the analysis of countermeasures 10 and 11, which involve headway control for mitigating rear-end crashes, are D, T, V, and A, representing the headway distance, reaction time, traveling speed, and deceleration level, respectively. The example headway control system as analyzed here uses a headway time of 3 s such that $D = 3 \cdot V$. This means that: (1) there is a 3-s separation between vehicles and (2) the headway distance is a linear function of speed. The columns labeled "D (3V)" and "Vo" in table 35 indicate the speed/ headway distance relationship involved in this analysis.

The set of calculations for nominally good conditions use $T = 1$ s and $A = 16$ ft/s/s to represent an alert driver making a high deceleration stop. See the set of calculations in the upper third of the spread sheet (table 35). The results, shown in column M, indicate that there would be no crashes for speeds less than 40 mi/h and that the velocity of impact would be reduced considerably below the traveling speed at higher speeds.

In contrast, if an impaired driver is represented by a 3-s reaction time as is the case for the center third of table 35, there would be no reduction in travel speed at the time of the crash. This means that the countermeasure would not be effective if the driver were impaired.

On the other hand, the lower third of the table indicates that the countermeasure would do some good if the tire/road interface were slippery. (Column F is set to 4.8 ft/s/s.) Although the benefit is small, the countermeasure would help even if the driver were not aware that the road was slippery. If the road were slippery, the driver might set the headway control accordingly, but this possibility is not included in the benefits predicted here.

The countermeasure is intended to work in the dark. Hence the analysis given at the top of the table applies to dark situations. The benefits indicated in the top third of the table apply to dark situations.

Table 35. Analysis for countermeasures 10 and 11.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	vel.Vo mph	Vo ft/sec	Dsr ft.	D (3V)	T	A	D -Vo T	2A(D-Vo T)	Vo**2	Vs**2	Vs ft/sec	Vs mph	Delta V mph
2	5	7.3335	17.4	22	1	16	14.6665	469.328	53.78022225	-415.5477778	0	0	0.00
3	15	22.0005	69.2	66	1	16	43.9995	1407.984	484.0220003	-923.9619998	0	0	0.00
4	25	36.6675	143.3	110	1	16	73.3325	2346.64	1344.505556	-1002.134444	0	0	0.00
5	35	51.3345	240	154	1	16	102.6655	3285.296	2635.23089	-650.0651098	0	0	0.00
6	45	66.0015	359	198	1	16	131.9985	4223.952	4356.198002	132.2460022	11.49982618	7.840612384	4.70
7	55	80.6685	500	242	1	16	161.3315	5162.608	6507.406892	1344.798892	36.67149973	25.00272702	15.00
8	65	95.3355	663	286	1	16	190.6645	6101.264	9088.85756	2987.59356	54.65888364	37.26657369	22.36
9	75	110.0025	850	330	1	16	219.9975	7039.92	12100.55001	5060.630006	71.13810516	48.5021512	29.10
10													
11	vel.Vo mph	Vo ft/sec	Dsr ft.	D (3V)	T (alcohol)	A	D -Vo T	2A(D-Vo T)	Vo**2	Vs**2	Vs ft/sec	Vs mph	Delta V mph
12	5	7.3335	17.4	22	3	16	-0.0005	0	53.78022225	53.78022225	7.3335	5	3.00
13	15	22.0005	69.2	66	3	16	-0.0015	0	484.0220003	484.0220003	22.0005	15	9.00
14	25	36.6675	143.3	110	3	16	-0.0025	0	1344.505556	1344.505556	36.6675	25	15.00
15	35	51.3345	240	154	3	16	-0.0035	0	2635.23089	2635.23089	51.3345	35	21.00
16	45	66.0015	359	198	3	16	-0.0045	0	4356.198002	4356.198002	66.0015	45	27.00
17	55	80.6685	500	242	3	16	-0.0055	0	6507.406892	6507.406892	80.6685	55	33.00
18	65	95.3355	663	286	3	16	-0.0065	0	9088.85756	9088.85756	95.3355	65	39.00
19	75	110.0025	850	330	3	16	-0.0075	0	12100.55001	12100.55001	110.0025	75	45.00
20													
21	vel.Vo mph	Vo ft/sec	Dsr ft.	D (3V)	T	A (slippery)	D -Vo T	2A(D-Vo T)	Vo**2	Vs**2	Vs ft/sec	Vs mph	Delta V mph
22	5	7.3335	17.4	22	1	4.8	14.6665	140.7984	53.78022225	-87.01817775	0	0	0.00
23	15	22.0005	69.2	66	1	4.8	43.9995	422.3952	484.0220003	61.62680025	7.850273896	5.352337831	3.21
24	25	36.6675	143.3	110	1	4.8	73.3325	703.992	1344.505556	640.5135562	25.30836929	17.25531417	10.35
25	35	51.3345	240	154	1	4.8	102.6655	985.5888	2635.23089	1649.64209	40.61578622	27.69195215	16.62
26	45	66.0015	359	198	1	4.8	131.9985	1267.1856	4356.198002	3089.012402	55.5788845	37.89383275	22.74
27	55	80.6685	500	242	1	4.8	161.3315	1548.7824	6507.406892	4958.624492	70.41750132	48.01084156	28.81
28	65	95.3355	663	286	1	4.8	190.6645	1830.3792	9088.85756	7258.47836	85.19670393	58.0873416	34.85
29	75	110.0025	850	330	1	4.8	219.9975	2111.976	12100.55001	9988.574006	99.9428537	68.14130613	40.88

For the rear-end type of crash there are several modes of crashing: the lead vehicle could have been stopped for a relatively long time, the lead vehicle could have stopped suddenly, or the lead vehicle could still be moving. Accident data indicate that well over 50 percent of the rear-end crashes are of the first mode, involving already stopped vehicles.

Rather than treating all of these different modes, we have treated all cases as if they were the worst case, namely the lead vehicle stopped.

In the other cases, there is more braking distance because the lead vehicle moves forward while the trailing vehicle is stopping. Also, in the case of a crash with a moving lead vehicle, the relative velocity at impact is lower. In the case where the driver stops suddenly, the reaction time of the driver is key to whether a crash will occur. If the driver of the following vehicle applies the brakes at the same point as where the leading vehicle's brake lights came on, then assuming that the trailing vehicle decelerates at the same rate or higher than that of the leading vehicle, there will not be a crash. In summary, estimates of crash reductions based upon a stopped lead vehicle are conservative in the sense that these estimates would contain more crashes than would be obtained using estimates considering each of the different crash modes.

Based upon: (1) the distribution of traveling speeds associated with rear-end crashes as reported in NASS, (2) the numbers of PD, INJ, and FAT crashes in the CARDfile sample, and (3) a prediction of the influences of the deltaVs associated with the remaining crashes, a cost reduction of 70.2 percent is predicted for rear-end crashes if the countermeasure is very effective.[76] (See appendix F for a rundown of the calculations involved.) Table 36 summarizes the numbers of crashes involved and the costs associated with them. A key result for comparing this countermeasure with others is that a very effective headway control countermeasure would reduce the predicted overall crash cost by approximately 7.2 percent.

These predictions above are extraordinarily beneficial. The idea of eliminating 70 percent of the rear-end crashes is likely to seem completely impossible to people with experience in trying to influence the accident record. Given reasonable uncertainty that this countermeasure could be 100-percent effective, results are also given in table 36 for cases in which the countermeasure is assumed to be 50- and 25-percent effective in eliminating crashes. This practice is used in subsequent cases where a concept is predicted to be very effective in reducing the costs of a frequently occurring crash situation.

Since driver warning is involved, there are human performance questions as to how well drivers will be able to use the warning. Hence, there is a need to consider the effectiveness of the countermeasure from a human factors point of view.

Table 36. Headway control countermeasures (CM's 10 and 11).

	Without countermeasure				With countermeasure			
	PDO/Inj C	Injury A&B	Fatal	Total	PDO/Inj C	Injury A & B	Fatal	Total
Low-friction	4,304	380	0	4,684	2,430	219	0	2649
Alcohol	1,956	622	13	2,591	1,956	622	13	2591
All other rear-end crashes	28,469	3,033	23	31,525	4,625	372	2	4999
Total rear-end crashes	34,729	4,035	36	38,800	9,011	1,213	15	10239
Cost	$333,919,335	$753,104,505	$90,351,756	$1,177,375,596	$86,640,765	$226,397,959	$37,646,565	$350,685,289

					Effectiveness		
					100%	50%	25%
Reduction	PDO/Inj C	Injury A & B	Fatal	Total No.	Cost*	Cost	Cost
Number of crashes	25,718	2,822	21	28,561	$826,690,307	$413,345,154	$206,672,577
Percent change in rear-end	74.05%	69.94%	58.33%	73.61%	70.21%	35.11%	17.55%
Percent change in all accidents In CARDfile sample	14.80%	7.66%	1.64%	13.48%	7.20%	3.60%	1.8%

* cost of rear-end crashes by severity

PDO/Inj C -	$ 9,615
Injury A and B	$ 186,643
Fatal	$ 2,509,771

In general, and in this case specifically, an analysis based upon physical reasoning leads to more optimistic results than one might expect to obtain using predictions based upon proportioning schemes like those used for the cross-cutting countermeasures. The rationale justifying this difference is that when a physical argument is used, it is tacitly assumed that the analyst has compelling reasons for asserting that certain situations that previously led to crashes are now very unlikely to lead to crashes. For example, if the countermeasure causes the vehicle to stop before a crash can occur, it is presumed that there are no extenuating circumstances that would cause the crash to occur. Consequently, the physically based analyses tend to produce more optimistic results for situations in which the countermeasures are effective than if the predictions were to be based upon proportioning of the associated factors.

Countermeasures 8 and 9 pertaining to objects on the road, including pedestrians, involve sensing and braking. In these cases, the analysis has proceeded from a design analysis situation in which the maximum range at which the object, person, or animal in the road is sensed is no more than 150 ft. For nominal driving conditions the analysis uses a response time of 1 s and a deceleration capability of 0.5 g (16 ft/s/s). Calculations for impaired (drunk or drugged) drivers indicate that these countermeasure systems will not be effective in those situations. These systems are expected to be effective in the dark. Their effectiveness will be limited when the road is slippery and the loss in effectiveness is accounted for by using a deceleration capability of 4.8 ft/s/s. Given the assumptions listed above, table 37 indicates that countermeasure 8 is predicted to reduce the costs of pedestrian, animal, and cyclist crashes by approximately 53.4 percent, which amounts to approximately a 3.4-percent reduction in the cost of all crashes. Supporting calculations are in appendix F.

For countermeasure 9 pertaining to the pedestrian port, table 38 shows that the predicted percentage savings would be very small for this system. We believe that this countermeasure is only likely to be worthwhile as a spot improvement for locations where special safety problems are known to exist or are deemed to be likely.

The benefits in terms of cost reductions for crashes are substantial for pedestrian, animal, and cyclist crashes because many of these crashes occur at low speed and the braking countermeasures are particularly effective at low speed. There are enough of these types of crashes to make countermeasure system 8 worthwhile from an overall sense, although the headway control countermeasure is predicted to be much more effective in providing safety benefits.

Table 37. Pedestrian/cyclist/animal in the roadway (CM 8).

	Without countermeasure				With countermeasure			
	PDO/Inj C	Injury A & B	Fatal	Total	PDO/Inj C	Injury A & B	Fatal	Total
Low friction	414	69	4	487	256	50	6	312
Alcohol	123	135	26	284	123	135	26	284
All other ped/cyc/animal	7,324	2,872	145	10,341	1,978	1,066	59	3103
Total ped/cyc/animal	7,861	3,076	175	11,112	2,357	1,251	91	3699
Cost	$42,496,566	$264,068,448	$420,063,875	$726,628,889	$12,741,942	$107,395,848	$218,433,215	$338,571,005

Reduction	PDO/Inj C	Injury A & B	Fatal	Total No.	Cost*
Number of crashes	5,504	1,825	84	7,413	$388,057,884
% change in ped/cyc/animal	70.02%	59.33%	48.00%	66.71%	53.41%
% change in all accidents In CARDfile sample	3.17%	4.95%	6.32%	3.50%	3.38%

* Cost of ped/cyclist/animal crashes by severity

PDO/Inj C -	$5,406
Injury A and B	$85,848
Fatal	$2,400,365

Table 38. Analysis for countermeasure 9.

Reduction Crash Type	Severity	NT	NQ	$(NQ/NT)^2$	No. of Crashes	Cost*
Pedestrian	PDO/Inj C	$7,861	405	.00265	21	$112,800
	Inj A & B	3,076	158	.00264	8	696,720
	Fatal	175	9	.00264	0	1,111,026
Total		$11,112	572		29	1,920,545
% of all crashes					.01%	.02%

* Costs/Crash

	PDO/Inj C	Inj A&B	Fatal
Ped/Cyclist/Animal	9,417	211,533	2,714,982

(See appendix A for a derivation of the Nq/Nt method used here.)

The total number of crashes, Nt, is the number of Pedestrian/Cyclist/Animal crashes. The number of "questionable" crashes Nq in this case is: the number of pedestrian crashes that occurred at non-intersections where the pedestrian was crossing the road, rather than walking along it.

This is estimated by using the portion of ped/cyclist/animal crashes that (1) involve pedestrians (28 percent), (2) were not at an intersection (58 percent of ped) and (3) occurred in urban areas (31.7 percent). Urban area was selected because pedestrians in urban areas generally do not walk along the street. Furthermore, the ped-port countermeasure would most likely be used in urban or suburban areas. Accordingly, we estimate that 5.15 percent of the ped/cyclist/animal accidents could possibly be affected by this countermeasure.

<u>Countermeasures involving running off the road (CM's 5, 6, and 7)</u>

The following analyses are separated into results for tangent (straight) sections of roadway and for horizontal curves. This is because the angle of departure used in the analyses is much larger for curved sections than it is for straight sections (0.06 radians versus 0.02 radians).

Table 39 shows results for a countermeasure in which there is no steering intervention. A warning is given when the driver runs off the road. It is assumed that the driver steers manually and successfully in 50 percent of the cases on tangent sections and 17 percent of the time on curved sections. If the driver does not steer, it is assumed that the brakes are applied and that the deceleration level is 0.25 g. The distance to objects or rollover mechanisms is 10 ft off the road in situations where there are run-off-road crashes. Taking these factors as representative, a countermeasure of this type (which was derived from countermeasure system 5, but without the steering correction and with braking) was predicted to be very beneficial. The predictions indicate that the costs of run-off-road crashes would be reduced by 48 percent, which would amount to a 10.6-percent reduction in all crashes. The supporting calculations are in appendix G.

These are predictions of extraordinary benefits, and so, results are also given in table 39 to indicate the sensitivity of these results to the effectiveness of the countermeasure.

We have tried many variations of countermeasure 6 in which there is a look-ahead capability for predicting run-off-road situations. This capability could be used to give advanced warning of possible run-off-road situations. Two prediction possibilities are: (1) to use a linear extrapolation from forward and lateral measurements or (2) to use the equations for a circle to make predictions for curved paths. The circular path choice is more conservative, but it is difficult to avoid giving false alarms on circular curves that typically occur on interstate quality roads. In order to eliminate false alarms, it may be necessary to give warnings that are only about 1 s ahead of running off the road. On the other hand, if straight line extrapolations are used, there can be situations in which the vehicle is about to run off the road before a warning is given. Perhaps the solution is to have a path-following system that would guide the vehicle into and around circular turns. It appears that other types of countermeasure systems will not be universally effective, but of course they may be less expensive to implement than a complete control system.

Table 39. Lateral lane-edge detection warning and steering correction for run-off-the-road crashes (CM 5).

	Without Countermeasure				With Countermeasure			
	PDO/Inj C	Injury A & B	Fatal	Total	PDO/Inj C	Injury A & B	Fatal	Total
Tangent sections								
Alcohol	3,401	2,102	97	5,600	3,401	2,102	97	5,600
Those involving braking	6,656	1,912	55	8,623	297	68	2	367
Those involving steering	6,656	1,912	55	8,623	0	0	0	0
Total ROR on tangent sections	16,713	5,926	207	22,846	3,698	2,170	99	5,967
Horizontal curves								
Alcohol	1,410	1,053	92	2,555	1,410	1,053	92	2,555
Those involving braking	3,855	1,291	40	5,186	2,167	590	18	2,775
Those involving steering	790	265	8	1,063	0	0	0	0
Total ROR on horizontal curves	6,055	2,609	140	8,804	3,577	1,643	110	5,330
Total ROR crashes	22,768	8,535	347	31,650	7,275	3,813	209	11,297
Cost*	$144,303,584	$1,463,829,315	$916,380,849	$2,524,513,748	$47,218,100	$680,719,221	$583,631,607	$1,311,568,928

					Effectiveness		
					100%	50%	25%
Reduction	PDO/Inj C	Injury A & B	Fatal	Total No.	Cost*	Cost	Cost
Number of crashes	15,493	4,722	138	20,353	$1,212,944,820	$606,472,410	$303,236,205
Percent change in ROR crashes	68.05%	55.33%	39.77%	64.31%	48.05%	24.02%	12.10%
Percent change in all crashes							
In CARDfile sample	8.92%	12.81%	10.77%	9.61%	10.56%	5.28%	2.64%

* Cost of run-off-the road crashes by severity

PDO/Iinj C -	$ 6,338
Injury A and B	$ 171,509
Fatal	$ 2,640,867

Based on the discussion above and the work referred to there, the following revised version of countermeasure 6 is presented here. The forward-looking sensor looks slightly off straight ahead by perhaps less than 1 ft in 100 ft. The sensor does not need to have a range of greater than about 100 ft. This is because there would be false alarms on circular curves if the device issued warnings when the forward distance to the road edge were greater than about 76 ft. To understand this, the equations for a circular curve need to be examined. As illustrated in figure 61, the forward distance x1 is a function of the lateral distance y1 and the radius R. The basic equations are as follows:

$$R^2 = X^2 + Y^2 \tag{14}$$

$$x1 = X \text{ and } Y = R - y1 \tag{15}$$

$$\text{hence } x1^2 = 2\,R\,y1 - y1^2 \tag{16}$$

Using these equations for a four-degree turn, that is, a curve with a radius of 1430 ft, and a lateral offset y1 = 2 ft, yields a longitudinal distance of 76 ft. This means that a vehicle traversing this turn would be within 76 ft of running off the road. Since four-degree turns are sometimes included, even in interstate-quality roads, the maximum range for warnings might be 76 ft. Otherwise, warnings might be given when x1 is less than 2 s times the velocity. This would provide from about 1 to 2 seconds of advanced warning that the vehicle was about to leave the road. The rule for issuing a run-off-the-road warning would be as follows:

Issue a warning if $x1 \leq$ minimum of {76 or 2*V}.

The difference between this countermeasure and countermeasure 5 is seen as the additional warning of about 1 s or more in all cases, whether the road be straight or curved. In the following, we have estimated that 75 percent of the non-impaired drivers who are not traveling too fast for the conditions would have been able to steer to stay on the road regardless of whether on a curve or straight away. Accident reduction calculations can be found in appendix H.

In summary, countermeasure 6, if 100-percent effective, is predicted to reduce the cost of run-off-the-road crashes by approximately 53 percent and all crashes by about 11.7 percent. See table 40 for a breakdown of the factors contributing to this result.

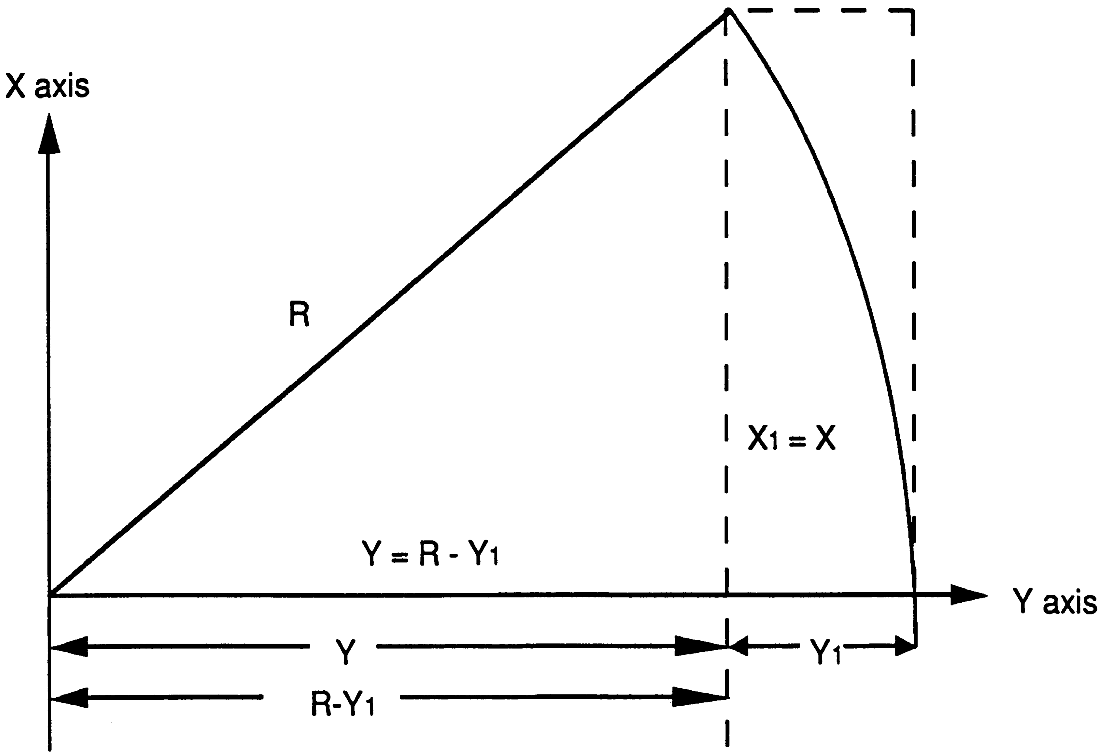


Figure 61. Path radius in relationship to x1 and y1.

Table 40. Lateral lane-edge detection warning and steering correction with lateral and longitudinal preview for run-off-the-road crashes (CM 6).

	Without countermeasure				With countermeasure			
	PDO/Inj C	Injury A &B	Fatal	Total	PDO/Inj C	Injury A &B	Fatal	Total
Tangent sections								
Alcohol	3,401	2,102	97	5,600	3,401	2,102	97	5600
Those involving CM6 braking	,984	2,868	82	4,312	169	18	0	187
Those involving CM6 steering cor.	3,328	956	289	12,934	0	0	0	0
Total ROR on tangent sections	16,713	5,926	207	22,846	3,570	2,120	97	5787
Horizontal curves								
Alcohol	1,410	1,053	92	2,555	1,410	1,053	92	2,555
Those involving CM6 braking	1,161	389	12	1,562	729	273	11	1013
Those involving CM6 steering cor.	3,484	1,167	36	4,687	0	0	0	0
Total ROR on horizontal curves	6,055	2,609	140	8,804	2,139	1,326	103	3,568
Total ROR crashes	22,768	8,535	347	31,650	5,766	3,489	207	9,462
Cost*	$144,303,584	$1,463,829,315	$916,380,849	$2,524,513,748	$36,544,908	$598,394,901	$546,659,469	$1,181,599,278

					Effectiveness		
					100%	50%	25%
Reduction	PDO/Inj C	Injury A & B	Fatal	Total No.	Cost*	Cost	Cost
Number of crashes	17,002	5,046	140	22,188	$1,342,914,470	$671,457,235	$335,728,618
Percent change in ROR crashes	74.67%	59.12%	40.35%	82.29%	53.19%	26.81%	13.40%
Percent change in all crashes							
In CARDfile sample	9.79%	13.69%	10.93%	10.47%	11.70%	5.85%	2.92%

* Cost of run-off-the road crashes by severity

PDO/Iinj C -	$6,338
Injury A and B	$ 171,509
Fatal	$2,640,867

The reason countermeasures 5 and 6 provide relatively comparable results is that they both employ braking when the vehicle runs off the road. This turns out to be very effective in these predictions. Perhaps drivers would prefer to stay on the road rather than stopping off the road, but the safety benefit is nearly equal.

It appears from our analyses and attempts to invent systems that would prevent running off the road that there is a need for a path-following system like that suggested for countermeasure 14. This would be for run-off-road as well as head-on situations. Path following would require a control unit that functioned continually to maintain the vehicle's path curvature close to the curvature of the road. For this purpose, a system that measured x1 and y1 as shown in figure 60 could be employed using the following version of equation 16:

$$1/R = 2*y1/(x1^2 + y1^2) \qquad (17)$$

The idea would be to use this equation as a preview of path curvature and to compare the previewed result with the predicted path of the vehicle result based upon vehicle dynamics. The difference between the predicted and previewed results would be used to determine the change in steering needed to reduce the difference to zero. This would require an estimate of the path curvature gain of the vehicle for small changes about its current operating point.

Countermeasure 7. Countermeasure 7 represents another approach to preventing run-off-the-road accidents. The idea is to give speed advisories if the road is slippery. A reason for not discussing this countermeasure at length is that it does not do much to the aggregate accident situation (Appendix I). The results given in table 41 show that this countermeasure would produce benefits of 2 percent for all run-off-road crashes and 0.5 percent of all crashes. Nevertheless, it could be useful as a spot improvement on curves where run-off-road accidents are prevalent under slippery conditions. The results do show that this countermeasure would provide benefits of about 6.3 percent for run-off-road accidents on curves.

Since horizontal curves are super-elevated, the friction required to make the curve, even at high speed, is not large. This means that the speeds recommended by this countermeasure are still fairly large. Even so, there are not many of these crashes overall and when they do occur, many of them are of low severity. All of this adds up to a low net benefit relative to the costs of all accidents.

Table 41. Dynamic horizontal curve speed advisory run-off-the-road crashes on horizontal curves (CM 7).

	Without countermeasure				With countermeasure			
	PDO/Inj C	Injury A & B	Fatal	Total	PDO/Inj C	Injury A & B	Fatal	Total
Alcohol	1,410	1,053	92	2,555	1,410	1,053	92	2555
Wet conditions	661	204	3	868	615	196	1	812
Icy/snowy conditions	972	199	3	1,174	80	6	0	86
All others	3,012	1,153	42	4,207	3,012	1,153	42	4,207
Total ROR crashes on curves	6,055	2,609	140	8,804	5,117	2,408	135	7,660
Cost*	$38,376,590	$447,466,981	$369,721,380	$855,564,951	$32,431,546	$412,993,672	$356,517,045	$801,942,263

					Effectiveness		
Reduction	PDO/Inj C	injury A & B	Fatal	Total No.	100% Cost*	50% Cost	25% Cost
Number of crashes	938	201	5	1,144	$53,622,688	$26,811,344	$13,405,672
% change in ROR curve crashes	15.49%	7.70%	3.57%	12.99%	6.27%	3.13%	1.57%
% change in all ror crashes	4.12%	2.36%	1.44%	3.61%	2.12%	1.06%	.53%
% change in all crashes In CARDfile sample	.54%	.55%	.39%	.54%	.47%	.23%	.12%

* Cost of run-off-the road crashes by severity

PDO/Inj C	$6,338
Injury A and B	$ 171,509
Fatal	$2,640,867

Countermeasures involving head-on situations (CM's 12, 13, and 14)

The head-on situation is particularly difficult to address. Roads are built to provide enough sight distance for vehicles to stop for fixed objects in the road. However, this does not provide enough sight distance to see on-coming vehicles if they are in the wrong lane coming around a horizontal curve or over a crest vertical curve. Countermeasures 12 and 13 represent simple systems for allowing the driver to have a warning of a vehicle coming from the other direction. They are an attempt to allow the driver to see around and over curves. The idea is similar to the roadway with moving lights as proposed in the Japanese ARTS program, only at a much lower cost in this case.[77]

These countermeasures are evaluated on the basis of alerting drivers so that they can react in 1 s (or less) to the presence of a conflicting on-coming vehicle. The evaluation proceeds from a calculation of a swerving maneuver that produces a 6 ft lateral shift in 2 s.

The distance (Dh) required for this maneuver is a function of speed as shown in column c of table 42. The distance 2Dh covers the distance traveled by both the swerving vehicle and the other on-coming vehicle, including the reaction time of the swerving driver. The countermeasure is evaluated as successful if 2Dh is less than the stopping sight distance associated with the speed of travel. In other words, if the driver can see far enough to see the other vehicle and then swerve, the crash is avoided.

The results presented in table 42 show that between 20 and 50 mi/h, these crashes are still predicted to occur. Even so, the high-speed crashes are avoided as well as some low-speed cases. This means that approximately 56 percent of the fatal crashes on curves are predicted to be eliminated. (See table 43.)

Since the costs of crashes involving fatals are very high (and particularly so for head-ons because there is often more than one person killed in this type of fatal), these countermeasures are predicted to be fairly beneficial from even an overall perspective. Either of them is predicted to have a benefit equaling over 1 percent of the costs of all crashes and about 14 percent of the costs of all head-on crashes.

If this type of countermeasure were to be extended to include vehicle-to-vehicle or vehicle-to-roadway-to-vehicle communications, there would be the possibility of using a braking pulse to warn the conflicting drivers of the possibility of a head-on crash. This pulse could be short such that the driver would not respond until the pulse was over (perhaps something like a pulse duration of 0.5 s). This would alert other

Table 42. Head-on countermeasures 12 and 13.

	A	B	C	D	E	F
1	spread sheet for head-on CM,s					
2	Aymax	ft/s/s	9.6		Y CM (ft)	6
3						
4						
5	T driver or CM	s	1			
6						
7	T steer period	s	1.981161276			
8						
9						
10						
11	vel.Vo mi/h	Vo ft/s	Dh	2 Dh	Dsight	0=no Head-on
12	5	7.3335	21.86234621	43.72469243	143	0
13	15	22.0005	65.58703864	131.1740773	143	0
14	25	36.6675	109.3117311	218.6234621	143	1
15	35	51.3345	153.0364235	306.072847	240	1
16	45	66.0015	196.7611159	393.5222319	359	1
17	55	80.6685	240.4858084	480.9716167	500	0
18	65	95.3355	284.2105008	568.4210016	663	0
19	75	110.0025	327.9351932	655.8703864	850	0

1 mi/h = 1.61 km/h

1 ft = 0.305 m

Table 43. Head-on crashes on curves (CM 12 and 13).

	PDO/Inj C	Injury A & B	Fatals	Total
Total number of head-on crashes	4,994	1,858	195	7,047
Total number of head-on crashes on curves	1,514	585	58	2,157
% not occurring because of CM*	31.70%	30.50%	56.00%	
Number not occurring because of CM	480	178	32	690
Total cost** of head-on crashes	$49,665,330	$410,107,050	$597,733,500	$1,057,505,880
Total cost of head-on crashes on curves	$15,056,730	$129,124,125	$177,787,400	$$321,968,255
Reduction in cost due to CM	$4,772,983	$39,382,858	$99,560,946	$143,716,787

Reduction in:	PDO/Inj C	Injury A & B	Fatals	Total
Number of crashes	480	178	32	690
% head-on/curve crashes	31.70%	30.50%	56.00%	31.99%
% all head-on crashes	9.61%	9.60%	16.66%	9.79%
% all crashes in CARDfile sample	.28%	.48%	2.54%	.33%
Cost of crashes	$4,772,983	$39,382,858	$99,560,946	$143,716,787
% cost of all head-on/curve	31.70%	30.50%	56.00%	44.64%
% cost of all head-on	9.61%	9.60%	16.66%	13.59%
% cost of all in CARDfile sample				1.25%

* The crashes that still occur were identified by their travel speeds. The allocation of cases to the travel speeds was done by using the travel speed distribution of head-on crashes by severity from the NASS file.

** cost of head-on accidents

PDO/Inj C	$9,945
Injury A and B	$220,725
Fatal	$ 3,065,300

neighboring vehicles as well as alerting the drivers and slowing them down some so that everyone would be prepared to respond if an emergency avoidance action were to be needed.

Countermeasure 14. This countermeasure is based on the concept of a path-following system. It requires cooperative communication between the roadway and vehicles. At the least, the lane edges or a special stripe need to be painted and maintained so that optical systems can detect them reliably.

There is a need for the stripe to be detected at a distance ahead so the steering control will be stable and will be able to negotiate curves smoothly. Given an ability to follow a delineated path, this countermeasure system might be used to address both head-on and run-off-the-road situations. In that sense, it may be viewed as somewhat of a crosscutting countermeasure. In that spirit, it has been evaluated like the other crosscutting countermeasures by using the technique involving the number of crashes in question to develop a prediction of the percentage of savings. This technique (derivation in appendix A), while perhaps seeming esoteric, is represented by the following simple equation:

$$\% \text{ reduction} = Nq\,(Nq/Nt)/Nt = (Nq/Nt)^2 \tag{18}$$

Where Nq = the number of crashes effected by the countermeasure, Nq/Nt represents a measure of the effectiveness of the countermeasure based upon the idea that the effectiveness of the countermeasure is in proportion to the number of crashes in question divided by the total number of crashes of that type. The number of crashes saved or reduced in severity divided by the total number of crashes is equal to the predicted percentage of reduction in crashes.

The technique described above has been applied to both run-off-road and head-on crashes as illustrated in table 44. It was assumed that the countermeasure did not apply to situations associated with alcohol or slippery conditions. In hindsight, one might make a case for including at least some of the alcohol-related situations. Furthermore, a physical analysis would be likely to lead to a higher prediction of benefits. Nevertheless, the predictions in table 44 indicate that this type of countermeasure system would result in a 7.3-percent reduction in the costs of all crashes, which makes it a very beneficial countermeasure even in comparison to other types of crosscutting countermeasures.

Table 44. Analysis for countermeasure 14.

Reduction Crash Type	Severity	NT	NQ	$(NQ/NT)^2$	No. of Crashes	Cost*
Run-off-the-Road	PDO/Inj C	22,814	11,993	.27635	6,305	$39,958,250
	Inj A&B	8,548	4,148	.23548	2,013	345,223,139
	Fatal	347	140	.16278	56	149,167,127
Total		31,709	16,281		8,374	534,348,517
% of all crashes					3.95%	4.65%

Reduction Crash Type	Severity	NT	NQ	$(NQ/NT)^2$	No. of Crashes	Cost*
Head-on	PDO/Inj C	4,994	3,092	.38334	1,914	$19,038,609
	Inj A & B	1,858	1,029	.30672	570	125,787,233
	Fatal	195	100	.26298	51	157,194,872
Total		7,047	4,221		17,627	$302,020,714
% of all crashes					8.32%	2.63%

Reduction for countermeasure 14		
	Number of Crashes:	3.95% + 8.32% = 12.27%
	Total Cost:	4.65% + 2.63% = 7.28%

* Costs/Crash

	PDO/Inj C	Inj A & B	Fatal
Run-off-the-road	6,338	171,509	2,640,867
Head-on	9,945	220,725	3,065,300

From a technical standpoint this countermeasure requires a controller that will maintain a path-following function (as discussed previously in, *"Countermeasures Involving Running Off the Road (CM's 5, 6, and 7")*). In this case, the situation for predicting path curvature is indicated in figure 61. We can apply equation 17 again, but with x1 and y1 as indicated in figure 61.

The approach proposed is called a "previewer-predictor-corrector-accumulator" system. The basic features of the system are illustrated in figure 62. This system is based upon ideas derived from the theory of driving. The basic notion consists of comparing the previewed estimate of the path with the predicted path and then adjusting the steering control to correct the difference between the predicted and previewed path. In this case, it is envisioned that a co-driver would operate much like a human driver using previewer and predictor functions to form a difference that would be corrected by accumulating changes in steering commands.

<u>Countermeasures involving intersection situations (CM's 15, 16, 17, and 18)</u>

For this analysis, countermeasures 15, 16, and 17 have been combined into one composite countermeasure that would be applied at either two-way or four-way stops. That is, minor road and major road and both road warnings of approaching or waiting vehicles would be given as well as indicator lights indicating who was next to turn at four-way stops would be provided. This composite countermeasure would apply to both crossing-path and left-turn crashes at signed intersections.

It is presumed that: (1) the traffic flow is such that a signed intersection is deemed to be appropriate for these locations and (2) the objective of the countermeasure would be to improve safety even if individual vehicles might be delayed slightly.

Since left-turn crashes do not happen often at signed intersections, the contribution of left-turn situations to the benefits is small. Nevertheless, both crash types were analyzed. Table 45 provides predictions of benefits based upon the $(Nq/Nt)^2$ approach where the base set of accidents was the crossing-path set and the set of crashes being considered were those that occurred at signed intersections. The cost savings in crossing-path crashes is predicted to be 24.6 percent and the savings with respect to all crashes is predicted to be 2.8 percent. As indicated, an advanced treatment of all signed intersections is predicted to be quite beneficial (even though ideally the stop sign should be almost an entirely safe means for controlling flow at an intersection).

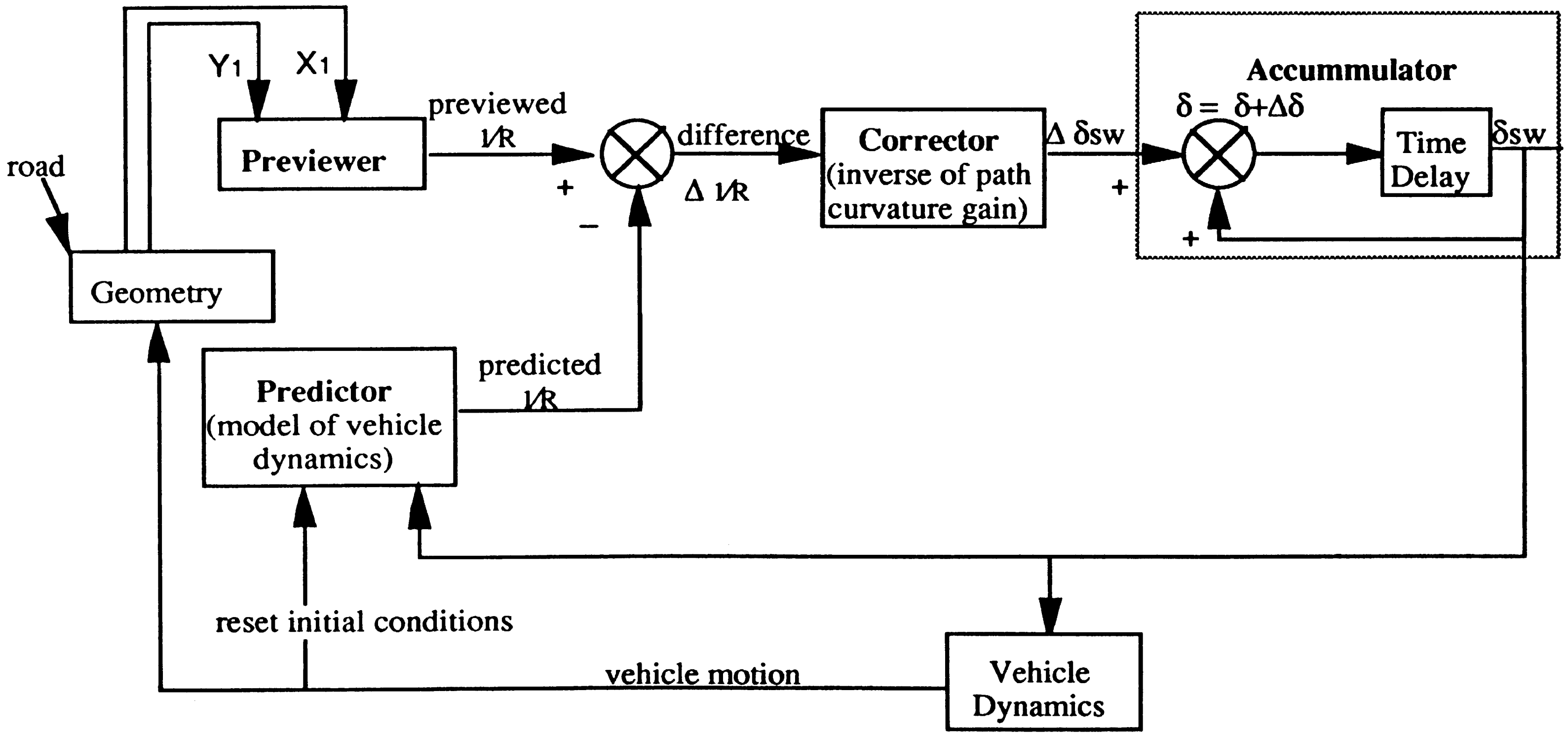


Figure 62. Diagram of a previewer-predictor-corrector-accumulator system.

Table 45. Analysis for countermeasures 15, 16, and 17.

Crash Type	Reduction Severity	NT	NQ	$(NQ/NT)^2$	No. of Crashes	Cost*
Crossing Path	PDO/Inj C	18,191	8,334	.20989	3,818	$35,955,306
	Inj A&B	4,183	1,891	.20437	855	180,831,182
	Fatal	99	63	.40496	40	108,846,097
Total		22,473	10,288		4,713	$325,632,585
% of all crashes					2.22%	2.84%

* Costs/Crash

	PDO/Inj C	Inj A & B	Fatal
Crossing Path	9,417	211,533	2,714,982

Countermeasure 18. This countermeasure applies to left turns at locations where vehicles stop to turn left to or from a main road to a driveway or side road. Table 46 indicates that the warning signs and presence location devices associated with this countermeasure will provide benefits of a 17.0-percent reduction in costs for left-turn crashes and an almost 1-percent savings for all crashes. These are worthwhile benefits but perhaps the benefit-to-cost ratio would be improved if this countermeasure were to be used in a spot improvement program in which likely crash sites are chosen for treatment.

Table 46. Analysis for countermeasure 18.

Crash Type	Reduction Severity	NT	NQ	$(NQ/NT)^2$	No. of Crashes	Cost*
Left Turn	PDO/Inj C	8,835	3,373	.14575	1,288	$13,174,763
	Inj A & B	2,452	1,030	.17645	433	89,171,847
	Fatal	40	16	.16000	6	17,300,762
Total		11,327	4,419		1,727	$119,620,371
% of all crashes					.82%	1.04%

* Costs/Crash

	PDO/Inj C	Inj A & B	Fatal
Left Turn	10,210	206,098	2,703,244

REVIEWS OF COUNTERMEASURE SCOPE AND BENEFITS

This summary section provides a generalized benefit evaluation for all of the countermeasures developed in this study.

Countermeasure 1. Night vision perceptual enhancement

Scope

- Problematic situation—This is a crosscutting countermeasure that address all six of the crash types selected for study. The crash situation involves dark, unlit situations that are frequently associated with all types of crashes.
- Modes of driving—The countermeasure is intended to aid in both the crash-prevention and crash-avoidance modes of driving. It may come into play during the speed-setting mode and provide the driver with the ability to discern objects better and may cause drivers to travel faster if drivers are not prudent when visibility is limited.
- Informational matters—As a vision enhancement, the countermeasure provides the driver with information that is not readily detected with the human eye. The countermeasure does not require any special information to function properly. The driver is required to interpret the image of the driving scene. The driver needs to view both the scene and the display. Hence, there could be so much information to view and process that the driver could feel overloaded.

Benefit

- Rationale/justification—It is clear that normal driving is highly dependent upon the ability to see. This countermeasure is based upon increasing the driver's ability to see and recognize hazards that otherwise might go unnoticed and thereby cause a crash.
- Assessment of potential cost-savings and effectiveness—Our analyses indicate that this countermeasure would reduce all accidents by 3.6 percent and accident costs by 7.3 percent. These are high potential benefits in our scheme for predicting benefits. Given our understanding of the current technology for creating night vision images, the countermeasure might not be completely effective. It seems that an estimate of 50-percent effectiveness might be a high expectation for systems using current technology

Countermeasure 2. Driver impairment warning

Scope

- Problematic situation—The driver is the problem in this case. For some reason the driver is not fit to drive. Reaction time is too long. Erratic steering behavior is typical. If alcohol or drugs are involved, fatal accidents are more likely, and dark, unlit situations are particularly likely to be associated with fatal crashes.

- Modes of driving—The concept of the countermeasure is to identify impaired drivers and prevent them from driving ("stop the vehicle, lock the doors, and call the police"). Given this concept, the driving mode is a mute point.
- Informational matters—The informational aspects of this countermeasure is pretty well mute, also.

Benefit

- Rationale/justification—Alcohol and drugs are associated with many severe crashes. Persons with reaction times above 2 s are exceptionally unalert and analyses indicate that 3-s reaction times would be disastrous. Drivers impaired to this level are not predicted to be able to meet the demands required for driving.
- Assessment of potential cost-savings and effectiveness—Although the number of crashes saved by a system for preventing impaired drivers is not high, the cost-savings are large because of the severity of the crashes involved. The reduction in overall accident costs is predicted to be 9.9 percent.

Countermeasure 3. Vehicle-based friction/ice detection and warning system

Scope

- Problematic situation—Icy or wet and slippery roads are associated with many crashes. Drivers who are unaware of the slipperiness of the road may be traveling too fast for the conditions.
- Modes of driving—This countermeasure applies to the first two modes of driving. The countermeasure provides an advisory speed to aid in setting the expected speed of travel. This advisory speed is based upon crash-prevention considerations. The idea is to avoid crash-avoidance situations before they develop.
- Informational matters—For a vehicle-based system, sensors on the vehicle need to detect the frictional potential of the road. It seems impractical to gather this information at any significant distance ahead of the vehicle. Hence, the information needs to be acted on quickly as well as prudently in order to attain an appropriate speed.

Benefit

- Rationale/justification—The number of crashes when roads are slippery due to environmental conditions is large enough to provide justification for this type of countermeasure.
- Assessment of potential cost-savings and effectiveness—This type of countermeasure is predicted to address 4 percent of all crashes and to reduce accident costs by 3.3

percent. Since the driver is not given warning until the vehicle is on a slippery surface, the countermeasure's effectiveness will be reduced. The driver may already be going too fast for conditions. For this reason, we estimate that the effectiveness of this countermeasure system would be no more than 33 percent.

Countermeasure 4. Roadside friction/ice detection and warning system

Scope

- Problematic situation—This is the same as for countermeasure 3.
- Modes of driving—This is the same as for countermeasure 3.
- Informational matters—In this case,with roadside hardware used to detect friction, the quality of information may be better than that obtained from a vehicle-based system. The information will be obtained in a more timely manner with respect to when the driver needs it in order to have space to slow down. Furthermore, it will be available to all drivers through signing. This means that the vehicles do not need to be equipped with special devices for the countermeasure to be beneficial. (In addition, the countermeasure will be available to everyone as soon as the system is installed. One does not need to wait for the countermeasure to penetrate the vehicle market.) The quantity of data involved is simply a speed advisory that should not overload the driver if it is presented well.

Benefit

- Rationale/justification—Same as countermeasure 3.
- Assessment of potential cost-savings and effectiveness—Although the predicted savings are 4 and 3.3 percent for the number of crashes and cost-savings (as for countermeasure 3), the effectiveness is likely to be much larger because the driver can be given advanced warning in this case. Since the driver need not enter the slippery area traveling too fast, the effectiveness of this countermeasure is estimated to be twice as much as that estimated for the vehicle-based system, that is, 6.6 percent.

Countermeasure 5. Lateral lane-edge detection and warning

Scope

- Problematic situation—A frequent type of crash involves running off the road and hitting a fixed object (for example, a tree) or rolling over. This situation is clearly initiated by the act of running off the road.
- Modes of driving—As with many countermeasures, this countermeasure primarily involves the crash-prevention mode of driving. It has an element of crash avoidance in the sense that a maneuver is implied and needed to keep the vehicle on the road. However, this can be a fairly mild maneuver if the driver is alerted soon enough. As amended for analysis, this countermeasure involves braking when the vehicle leaves

the road. This is clearly an intervention pertaining to the crash-avoidance mode of driving.

- Informational matters—The information sensed involves detecting the edge of the road. The quality of this information depends upon having good road-edge delineation. Data on the distance to the road edge needs to be accurate to within a few inches. However, the percentage accuracy need not be high because the range of the lateral sensor need only be about 3 ft. The warning given when the vehicle is on the road needs to be delivered quickly and for long enough for the driver to have a reasonable opportunity to respond.

Benefit

- Rationale/justification—The rationale for this countermeasure is that drivers will benefit from a warning if they are drifting off the road and, if they have not steered the vehicle back onto the road, the vehicle needs to be stopped before a rollover or fixed-object crash occurs.
- Assessment of potential cost-savings and effectiveness—The cost-savings for this countermeasure are predicted to be 10.6 percent of the cost of all crashes. This is in large part due to the braking feature of the countermeasure. In arriving at 10.6 percent, it was assumed that the driver steered back onto the road in 50 percent of the straightroad cases and 17 percent of the curved-road cases. In addition, there may be other factors to consider. This is a warning system first and the driver may not respond as desired. Perhaps the effectiveness of the warning feature of this countermeasure could be 25 percent on straight-aways and zero on curves—it is difficult to judge. Nevertheless, the braking action would still make the countermeasure very effective such that the overall cost-savings would lose no more than 1 or 2 percent.

Countermeasure 6. Lateral lane-edge detection and warning with longitudinal preview

Scope

- Problematic situation—The problem addressed is running off the road. (The problematic situation is the same as for countermeasure 5.)
- Modes of driving—This countermeasure pertains primarily to the crash-avoidance mode of driving because it focuses on the hazard of running off the road and it calls for action to prevent, first, running off the road, and second, to avoid crashes if the vehicle leaves the road.
- Informational matters—This countermeasure has all the informational factors described for countermeasure 5 plus those related to the longitudinal preview. The preview feature does not put any additional information processing demands on the driver beyond those associated with countermeasure 5. The longitudinal preview

requires detecting the road edge about 100 ft in front of the vehicle. This data does not need to be extremely accurate. It appears that ± 2 ft would be acceptable.

Benefit

- Rationale/justification—The rationale for this countermeasure is to provide an advanced system that uses preview to enhance the capabilities associated with countermeasure 5.
- Assessment of potential cost-savings and effectiveness—The cost-savings in this case are predicted to be 11.7 percent of all crash costs. The countermeasure is assumed to be 75-percent effective in keeping vehicles on the road on both horizontal curves and tangent straight-aways in arriving at the 11.7-percent figure. The influences of other factors may reduce the overall effectiveness of the countermeasure. Given that the driver needs to respond, the effectiveness of the warning may be about 50 percent rather than 75 percent. This could mean a drop in 1 to 2 percent in the overall costs. (The key cost-savings feature is to stop the vehicle if it does run off the road.)

Countermeasure 7. Dynamic horizontal curve speed advisory

Scope

- Problematic situation—Vehicles are known to run off the road at curve sites if they are traveling to fast for the conditions.
- Modes of driving—This is a crash-prevention type of countermeasure in that it attempts to either get drivers to control their speed or to intervene and control speed directly.
- Informational matters—The system detects the slipperiness of the curve and displays an advisory speed. Variable message signs and audio warnings are considered. In-vehicle signing is also proposed. The important quantity to get accurately is the friction level, especially in the range of friction from 0.3 to 0.1. The advisory is not considered to be so complicated as to overload the driver. Information on the super-elevation and curvature of the road are taken to be known and accounted for. The computational problems are trivial.

Benefit

- Rationale/justification—We currently have signs showing the presence of curves ahead and slippery road warnings. This countermeasure is aimed at turning these signs into real-time, variable message signs.
- Assessment of potential cost-savings and effectiveness—Because: (1) there are not many of the crashes of the type addressed, (2) the severity of crashes tends to be low when the road is slippery, and (3) curves are designed to use little side friction such that vehicles can be driven around them successfully at relatively high speed even if the road is slippery, this countermeasure provides low-cost benefits. A general

purpose slippery road countermeasure, such as those proposed for countermeasures 3 and 4, will do quite well. This countermeasure may be useful as a spot improvement at sites that are known or predicted to have bad accident records.

Countermeasure 8. Longitudinal control for pedestrians etc. in the roadway

Scope

- Problematic situation—There is an obstacle in the roadway and the driver is not aware of it and the driver is not responding to it.
- Modes of driving—This is a crash-avoidance situation.
- Informational matters—The primary information needed is data on the presence of an obstacle. The range at which this obstacle can be detected will determine how fast information needs to be processed by the driver. The need for braking needs to be communicated to the driver in a manner that will elicit prompt action.

Benefit

- Rationale/justification—After running off the road, hitting a fixed or slowly moving object on the road is the second most prevalent type of single-vehicle accident. This countermeasure is aimed at mitigating these situations.
- Assessment of potential cost-savings and effectiveness—The potential cost-savings are predicted to be 3.4 percent of all crashes. The fact that crashes with pedestrians often result in serious injuries or fatalities makes this a costly accident category. The effectiveness of the countermeasure needs to be considered. There may be technical difficulties in detecting items like people and animals. The drivers may have trouble responding as desired to the warnings. The effectiveness might be as low as 25 percent—it is difficult to say.

Countermeasure 9. Pedestrians at mid-block crosswalks

Scope

- Problematic situation—This countermeasure addresses the problem of crashes with pedestrians.
- Modes of driving—The countermeasure goes from the prevention mode of driving into the crash-avoidance mode. (It also advises pedestrians.)
- Informational matters—The information needed is the presence of a pedestrian. In this case, the pedestrian is identified positively so that the problem of recognizing pedestrians is avoided. The information is transmitted by signs that are easily understood. Drivers should have little difficulty in interpreting this information.

Benefit

- Rationale/justification—Since pedestrians are hard to detect and they are vulnerable to vehicle crashes, the reason for this countermeasure is to provide a system that would detect pedestrians and alert drivers to their presence.
- Assessment of potential cost-savings and effectiveness—This countermeasure was predicted to be the least effective one in reducing overall costs of crashes. It is a candidate for spot applications at locations where pedestrians cross sporadically, such as near schools.

Countermeasure 10. Headway control based upon adaptive cruise control

Scope

- Problematic situation. The problem addressed is rear end crashes where one vehicle runs into the rear of another vehicle that is either stopped or still moving.
- Modes of driving. The adaptive cruise control operates in a crash-prevention mode. If headway cannot be maintained, a crash-avoidance maneuver is required.
- Informational matters—The data needed for this countermeasure is the range and range rate to the vehicle ahead. The system processes this data and maintains headway automatically. The driver is relieved of processing information to maintain headway.

Benefit

- Rationale/justification—Rear-end crashes are very prevalent. Apparently drivers often fail to notice a vehicle ahead. This countermeasure is intended to provide the diligence that is needed to avoid rear-ending a vehicle ahead.
- Assessment of potential cost-savings and effectiveness—Rear-end accidents are very prevalent. This countermeasure is predicted to reduce the number of crashes by 13.5 percent—the most of any countermeasure. However, since many of the rear end crashes are not serious, the percentage change in accident costs is 7.2 percent. The effectiveness of this countermeasure depends upon either driver control or automatic braking. In the case of automatic braking, the effectiveness might be quite high, but liability considerations might make this approach unlikely. With driver control of braking, the effectiveness might be 50 percent or less.

Countermeasure 11. Headway control based on adaptive cruise control with braking

This has been incorporated with countermeasure 10. It would have been an automatic braking version of 10. And the benefits would be the same as those predicted for countermeasure 10.

Countermeasure 12. Cooperative warning of the presence of on-coming vehicles

Scope

- Problematic situation—This countermeasure addresses head-on crashes on horizontal or vertical curves.
- Modes of driving—This countermeasure applies to crash-avoidance situations when they develop. It does give drivers advanced warning so that they will be prepared to perform crash-avoidance steering actions.
- Informational matters—The information to be transmitted is the possibility of a head-on crash. In this case, the countermeasure depends upon roadside hardware and cooperative use of the headlights by drivers to transmit the presence information.

Benefit

- Rationale/justification—The countermeasure attempts to use existing qualities of motor vehicles to provide advanced warning of the presence of an on-coming vehicle. In this case, the headlights are used as the source of the warning even in the daylight. The main rationale for this system is to provide a means for figuratively seeing around corners.
- Assessment of potential cost-savings and effectiveness—The countermeasure does not eliminate many crashes, but the cost of head-on crashes is large enough that a 1.2-percent savings in the total cost of all crashes is predicted. The effectiveness of this system might be only 25 percent or less until drivers begin to understand the system. This probably is best thought of as a spot improvement type of countermeasure.

Countermeasure 13. Warning of the presence of on-coming vehicles (road-based system)

Scope

- Problematic situation—This applies to the problem of head-on crashes on curves (as does countermeasure 12).
- Modes of driving—Same as 12, that is, crash avoidance.
- Informational matters—The data needed applies to on-coming vehicles. These vehicles are sensed by hardware in the roadway and the data is communicated upstream to vehicles coming the other way. This is like countermeasure 12, but in this case there is no need for cooperation from drivers turning on their headlights.

Benefit

- Rationale/justification—The main rationale for developing this type of countermeasure is to provide drivers with the type of information that they would obtain if they could see over hills or around corners. Also, in this case, the idea is to avoid requiring cooperation from drivers.

- Assessment of potential cost-savings and effectiveness—The benefits in cost-savings in this case is predicted to be 1.2 percent —the same as it was for countermeasure 12. However, in this case the drivers do not need to cooperate and the benefits could be forthcoming as soon as the hardware was installed in the roadway. The effectiveness might be 50 percent. It is unlikely that it would reach anywhere near 100 percent because of the uncertainties associated with knowing where to go and what to do when faced with a head-on situation.

Countermeasure 14. Lane-keeping

Scope

- Problematic situation—Head-on and run-off-road crashes are characterized by vehicles leaving their intended lane of travel. The problem addressed here is to keep vehicles in their lane unless turn signals are used to indicate that the driver intends to leave the lane of current travel.
- Modes of driving—This is primarily a crash-prevention type of system. The idea is to avoid the need for crash-avoidance maneuvers.
- Informational matters—The information that needs to be used is the path of the road ahead. The source of this information needs to come from the roadway itself. The ability to receive this information accurately and dependably in a timely manner is key to satisfying the needs of this system. The system is intended to operate automatically in a co-driver mode with the need for information exchange between the driver and the co-driver being minimal.

Benefit

- Rationale/justification—The rationale for this countermeasure is that drivers are deemed to need warnings and steering corrections to keep them from inadvertently leaving their expected lane of travel. A basic idea here is that drivers may become inattentive and that they would benefit from a backup system that aided them in improving their lane-following performance.
- Assessment of potential cost-savings and effectiveness—The potential cost-savings is predicted to be 7.3 percent for this countermeasure. This is likely to be a low estimate because of the inherent use of a relatively low effectiveness in making the estimate. That effectiveness was approximately 25 percent. The effectiveness might be increased to close to 100 percent for roadways that are designed for lane following and access limited to vehicles with the lane-following equipment. However, this would amount to a spot or facility type of improvement and the cost of developing the facility would be large.

Countermeasure 15. Warning of the presence of vehicles on a major road

Scope

- Problematic situation—The situation involved here is a driver on a minor road stopped at an intersection with a major road. The situation involves a stop or yield sign. The driver's problem is not to pull out into on-coming vehicles as well as not running the stop or yield sign in the first place.
- Modes of driving—This is a crash-prevention type of countermeasure.
- Informational matters—The new information added by this countermeasure is the presence of threatening vehicles on the major road. The information is detected by hardware in the roadway and transmitted to the driver via icons displayed at the intersection.

Benefit

- Rationale/justification—The reason for this countermeasure is to create a system that will aid drivers in determining when it is unsafe to enter a signed intersection. (The driver will need to take the ultimate responsibility for deciding when it is safe.)
- Assessment of potential cost-savings and effectiveness—The potential cost-savings of this countermeasure was not evaluated directly because the available crash data could not be separated into this type of crash alone. Instead, this countermeasure was combined with the other countermeasures applying to signed intersections in order to get an overall countermeasure for signed intersections (that is, countermeasures 15, 16, and 17 were combined into one). The potential savings from this signed intersection countermeasure is predicted to be 2.8 percent. The main source of benefits has to do with crossing-path types of crashes since left turns are a limited problem at signed intersections. The effectiveness of these warning systems might be 50 percent at the most since drivers are still required to make the final judgment and they will make some of the same mistakes they always have. Nevertheless, they will have the benefit of a backup system letting them know of the presence of hazards on their crossing paths.

Countermeasure 16. Warning of the presence of vehicles on a minor road

Scope

- Problematic situation—The situation here involves a warning of a crossroad ahead. The typical static signs used now do not tell if there is a vehicle at or approaching the intersection.
- Modes of driving—This is a crash-prevention countermeasure.

- Informational matters—The information needed pertains to the presence of vehicles on a minor road. The information is conveyed to the driver by a changeable message sign that operates in real time.

Benefit

- Rationale/justification—The purpose of this system is to provide drivers with real time warnings of the presence of potential conflicts with vehicles on side roads.
- Assessment of potential cost-savings and effectiveness—(See the comparable discussion given for countermeasure 15.)

Countermeasure 17. Four-way stop right-of-way indicators

Scope

- Problematic situation—Stop signs do not always prove to be 100-percent effective in preventing crashes. Common problems are drivers running the stop sign or drivers stopping and then entering the intersection at the wrong moment. The solution suggested by this countermeasure is to provide an aid for determining which vehicle is to use the intersection next.
- Modes of driving—This is a crash-prevention countermeasure.
- Informational matters—The information used is the order of arrival of vehicles at a four-way stop. This can be particularly difficult to keep track of for situations where there is more than one lane of travel in one or more directions. The system would process the arrival data to display who has the right of way, thereby relieving the drivers from trying to sort this out. The system would also serve the role of making the intersection and its stop signs more noticeable to drivers, both those that might run a stop sign and those that might pull out inappropriately.

Benefit

- Rationale/justification—The rationale for this countermeasure is to provide an effective system for controlling intersections such that only one vehicle at a time or vehicles from one direction will use the space incorporated in the intersection.
- Assessment of potential cost-savings and effectiveness—(See countermeasure 15 for a discussion of the safety benefits of the treatment of signed intersections.)

Countermeasure 18. Warnings for left turns

Scope

- Problematic situation—Drivers wanting to make left turns are often put in the difficult position of having to decide whether it is safe. They need to look in three directions and judge whether they can make the turn safely. Also, vehicles coming from the rear may be surprised to find vehicles waiting to turn into driveways and side roads.

- Modes of driving—This is a crash-prevention type of countermeasure.
- Informational matters—Drivers of vehicles approaching a left-turning vehicle need to be aware of it. This data would be conveyed to drivers by signs indicating the presence of vehicles turning left. Drivers would be provided with simple displays providing them with information that they might otherwise miss.

Benefit

- Rationale/justification—Left turns do not show up as a large problem at signed intersections. They do show up as a problem at signalized intersections. Many of the crashes appear to occur when drivers are turning from a main road into driveways. The purpose of this system is to do something to improve the safety of these situations.
- Assessment of potential cost-savings and effectiveness—The potential savings in the costs of all crashes is 1 percent for this countermeasure system. The effectiveness is likely to be no more than 50 percent because drivers will still tend to make poor judgments and lack-of-attention errors (just not as frequently as they did before). These estimates are likely to be less than those that would be predicted if left-turn crashes at signalized intersections were to be alleviated effectively. Perhaps the new signals with protected left-turn phases will alleviate the left-turn-at-intersection problems. In hindsight, a general protected left-turn countermeasure would have been interesting to consider at least for use in the spot-improvement context.

Summary of potential safety benefits

A summary comparing the potential safety benefits of all the countermeasure systems is presented in table 47. The method of analysis is identified, and the potential safety benefits are given for efficiency levels of 100 percent, 50 percent, and 25 percent. Only one level of efficiency is given for those countermeasures where the benefits were estimated by the generic (NQ/NT) method because a measure of efficiency is already inherent in the method itself.

The generic method for estimating effectiveness was developed out of necessity when it was extremely difficult to capture all the relevant factors necessary for the physical analysis of a large set of crashes of a certain type. It was much less labor-intensive than the various other methods used in this part of the research. If the results of this method were similar to those obtained by the analytical methods, then it would be a useful "first-cut" technique for estimating potential benefits of proposed countermeasures.

Table 47. Countermeasure benefits.

CM	SYSTEM	CRASH TYPE	ESTIMATION METHOD	100 % EFF. CRASH REDUCTION	100 % EFF. COST REDUCTION	50 % EFF. CRASH REDUCTION	50 % EFF. COST REDUCTION	25 % EFF. CRASH REDUCTION	25 % EFF. COST REDUCTION
CM1	Night Vision Enhancement	All	Prorated Distribution 1	3.57%	7.29%	1.79%	3.65%	.89%	1.82%
CM2	Impaired Driver Warning	All	Prorated Distribution 1	1.20%	9.86%	.60%	4.93%	.30%	2.47%
CM3/4	Low Friction Detection	All	Prorated Distribution 2	4.02%	3.25%	2.01%	1.63%	1.01%	.81%
CM5	Lateral Lane Edge Detection	Run-Off-Road	Del V/Brake & Steering	9.44%	10.56%	4.72%	5.28%	2.36%	2.64%
CM6	Lateral Lane Edge Det/Preview	Run-Off-Road	Del V/Brake & Steering	10.47%	11.70%	5.23%	5.85%	2.62%	2.93%
CM7	Hor. Curve Speed Advisory	Run-Off-Road	Travel Speed 1	.54%	.47%	.27%	..24%	.14%	.12%
CM8	Long. Control For Obj. In Rd.	Ped/Cycl/An	Del V/Braking	3.50%	3.38%	1.75%	1.69%	.88%	.85%
CM9	Pedestrian Det. At Midblock	Ped/Cycl/An	Nq/Nt	.01%	.02%	xxxx	xxxx	xxxx	xxxx
CM10/11	Headway Control	Rear-End	Del V/ Braking	13.48%	7.20%	6.74%	3.60%	3.37%	1.80%
CM12/13	On-Coming Vehicle Warning	Head-On	Travel Speed 2	.33%	1.25%	.17%	.63%	.08%	.31%
CM14	Lane Keeping	Head-On/Ror	Nq/Nt	12.27%	7.28%	xxxx	xxxx	xxxx	xxxx
CM15+16+17	Cooperative Intersection	Cross. Paths	Nq/Nt	2.22%	2.84%	xxxx	xxxx	xxxx	xxxx
CM18	Left-Turning Vehicle Warning	Left Turn	Nq/Nt	.82%	1.04%	xxxx	xxxx	xxxx	xxxx

Accordingly, the potential benefits in terms of crash reduction and cost reduction were calculated by the generic method and compared to those obtained by the analytical methods. Table 48 shows potential benefits of the countermeasures determined by the generic method (appendix I). Comparing these values with those in table 48 shows that the generic estimates are similar enough to the other estimates to be useful.

Table 48. Countermeasure benefits estimated by the generic method.

CM	System	Crash Type	% Reduction In Crashes	In Cost
CM1	Night Vision Enhancement	All	3.78%	6.71%
CM2	Impaired Driver Warning	All	1.33%	5.69%
CM3/CM4	Low Friction Detection	All	1.71%	1.24%
CM5	Lateral Lane-Edge Detection	Run-Off-Road	8.32%	7.54%
CM6	Lateral Lane-Edge Det/Preview	Run-Off-Road	8.32%	7.54%
CM7	Hor. Curve Speed Advisory	Run-Off-Road	.58%	3%
CM8	Long. Control for Obj. in Rd.	Ped/Cycl/An	4.98%	5.05%
CM9	Pedestrian Det. at Midblock Cross.	Ped/Cycl/An	.01%	. 02%
CM10/CM11	Headway Control	Rear-End	15.97%	7.60%
CM12/CM13	On-Coming Vehicle Warning	Head-On	.31%	.85%
CM14	Lane-Keeping	Head-On/ROR	12.27%	7.28%
CM15+CM16+CM17	Cooperative Intersection	Cross. Paths	2.22%	2.84%
CM18	Left-Turning Vehicle Warning	Left Turn	.82%	1.04%

CHAPTER 7. APPLICATION OF RESULTS TO THE CONSIDERATION OF COUNTERMEASURE IMPLEMENTATION

The foregoing discussion and analysis has identified 19 concepts for countermeasure systems that, in general, do not exist today. The development and implementation of systems requiring roadside installation obviously depends upon the initiative of highway agencies and those corporations that supply equipment for highway application. Although installations would be publicly funded, some degree of private investment must be made in product development and must be recouped through sales. For countermeasures that may be sold directly to the consumer as automotive products, the development, manufacturing, and marketing of the systems will be executed by industrial organizations, again with pricing that reflects their costs of development.

Regardless of the nature of the organization conducting the development and implementation, costs will constitute a paramount concern. The section entitled,"*Estimates of Countermeasure Cost,*" will discuss the basis for estimating costs for each countermeasure, although it is recognized that much is unknown at the current stage since only concept definition is available. We also note that a variety of system types have been defined as possible countermeasures, some of which involve systems autonomous to the vehicle, others operate autonomously at the roadside, and some require an interaction between an equipped vehicle and an equipped roadside in various ways. Thus, the section entitled, "*The Influence of Generic System Type on the Dynamic of Penetrating the Population,*" is presented as an initial consideration of the dynamics of implementation, noting that the utility of the interactive systems at any point in time depends upon the extant penetration of the equipment into the population of road sites and/or vehicles.

ESTIMATES OF COUNTERMEASURE COST

Chapter 5 of this report provided some commentary on the subject of relative cost, especially in terms of the sensing and processing elements associated with each countermeasure. In the following presentation, an estimate of the absolute cost of most, but not all, of the countermeasures is provided. The estimates are based upon: (1) the current price of some system products that are now appearing on the market and that differ only modestly, if at all, from the exact definition of the countermeasure, (2) the results of a delphi technique of expert cost estimation that has been reported in the literature, or (3) a simple breakdown of the roadside-type countermeasure systems into more-or-less conventional components and labor elements.[78]

In estimation method (2), data were collected by the University of Michigan in the Delphi II Study of IVHS, providing measures of expert opinion based upon a two-stage survey of IVHS leaders in industry and government. Each of the group of 55 experts estimated the calendar year of introduction and the sale price for production quantities of a wide array of IVHS functions. Survey questions were formulated with the aid of a small group of experts, presented to the larger group for response, and the resulting data tabulated as the first-round results. These results were then presented to all of the respondents so that each could review his or her previous estimates in light of the entire group's views, whereupon a second round of estimates was obtained and the results analyzed and presented in the report.

Concerning the roadside-type countermeasures, estimates were based upon individual costs normally seen in the installation of traffic control devices in Michigan. Countermeasures 12, 13, and 15 through 18 involved differing applications of fairly common signs, signals, processors, detectors, and wiring, thus making it possible to arrive at rough cost projection assuming that conventional purchase and installation rates apply. Of course, in these and all countermeasure concepts, the cost of the front-end development effort, including software development, is very difficult to estimate and is not included in the projection of costs for roadside systems.

Each of the countermeasures will be discussed in turn, below, beginning with a listing of the equipment required (also presented previously in chapter 4).

<u>Countermeasure 1. Night vision enhancement</u>

Equipment needed

- Infrared or other sensing system for producing an image of the driving scene.
- "Head-up" or other type of display for presenting the image to the driver.
- Image range detector—for estimating the range at which objects can be discerned in the display.
- Advisory speed display.
- Sensors for vehicle speed, tire/road friction, grade of roadway.
- Device for warning that speed exceeds the advisory discerning range.

Cost

The night-vision system only (without range estimation and warning) was predicted by the University of Michigan Delphi II Study to cost between $1150 to $1500 by the year 2010. A trade journal (*Automotive Industries Magazine*) has also reported that General Motors is developing an infrared night vision system whose estimated cost by the year 1994 may be in the range of $1000.

The authors have no knowledge, however, of any original-equipment motor vehicle that will be offered for sale with a night-vision option within the 1994 time frame. The additional function providing range estimation as a supplementary feature to nighttime imaging, per se, is probably similar in hardware requirements to the headway control package noted as countermeasure 10, and estimated by the Delphi II Study as costing $400 by the year 2004. Accordingly, the range of numbers given here suggest a total system cost in the range of $1,400 to $1,900.

Countermeasure 2. Driver impairment

Equipment needed

- Steering wheel angle sensor.
- Brake actuation sensor.
- Vehicle speed sensor.
- Processor for controlling warning based upon state of steering activity, vehicle speed, and brakes.
- Audible warning device.
- Flasher control and device for turning on the flashers.

Cost

This system has not been explicitly costed. Because most of the sensors, display, and switching components listed above are likely to appear in many vehicles as standard equipment supporting other functions (especially if braking and throttle actuation is available as drive-by-wire servomechanisms), it is believed that the principle costs will relate to the extensive development work needed to obtain highly reliable software, rather than in componentry, per se. Since current trends are toward artificial intelligence based upon some degree of fusion of sensory data, the costs will be exceedingly sensitive to production volume, as development costs are being recovered.

Countermeasure 3. Friction/ice detection and warning systems (vehicle based system)

Equipment needed

- Infrared or sonar detection system for determining sight distance.
- Advisory speed display.
- Sensors for vehicle speed, tire/road friction, grade of roadway.
- Device for warning if speed indicates overdriving of the friction-supportable range.

Cost

The vehicle-based implementation is unlikely to be viable soon. Systems that directly measure characteristics of road surface, such as SCAN 16, can currently be implemented only at the roadside.

Countermeasure 4. Friction/ice detection and warning systems (roadway mounted system)

Equipment needed

- Friction detector installed in the road.
- Processor for calculating speed advisories as well as low-friction messages.
- Wiring or local communications transmitters and receivers between friction detector, processors, and display.
- Advisory speed sign with dynamic speed display.

Cost

Many products for ice detection exist currently, but no general method for friction determination outside of the ice determination itself was identified. Costs for ice detection range from a few thousand dollars to $35,000 for a four-point detection with weather station and processing (see chapter 5, *"Sensing Technology Assessment"*). Also, significant advancment in cost estimation for robust means of friction assessment should be forthcoming from the DRIVE I - CROW Project and DRIVE II - ROSES Project. As for roadside display of a warning message, $2,000 is the nominal cost for a dynamic sign providing a roadside alphanumeric board.

Countermeasure 5. Lateral lane-edge detection warning and steering correction

Equipment needed

- Lane edge sensor for near-lateral proximity (3 ft. or less).
- A means of enhancing the lane boundary for the sensor.
- Processor for: (1) predicting running off the road based on distances to the lane edge and (2) making the decision on warning and/or control intervention, with generation of the control input command signal.
- Sensor for determining the vehicle motion vector.
- Means of inducing a path control input to steer-by-wire system.
- Warning device for indicating that the vehicle is too close to the edge of the road.

Cost

No cost data are available, since research on systems of this type has begun only recently. Since only very short range sensing is needed, the sensor may not be the cost-driver. If lane edge marking must be enhanced to achieve this functionality, the cost of vehicle-borne equipment will be supplemented by road-treatment costs and penetration of the vehicular systems into the vehicle population will depend in some measure on the extent of deployment of the roadside enhancement (see also chapter 7, *"The Influence of Generic System Type on the Dynamic of Penetrating the Population"*).

Countermeasure 6. Lane-edge detection warning and steering correction with lateral and longitudinal preview

Equipment needed

- Longitudinal and lateral lane-edge sensors.
- A means of enhancing the lane boundary for the sensor.
- Processor for: (1) predicting running off the road based on distances to the lane edge and (2) generating warnings and steering commands.
- Warning device for indicating that the vehicle is too close to the edge of the road.
- Steering actuator that can apply limited steering torque for swerving. (This torque might be limited to no more than 2 or 3 ft-lb, measured at the steering wheel.)

Cost

Currently no information on costing is available. Since this system must look well ahead of the vehicle in order to anticipate lane orientation in advance, a higher level of sensor performance is anticipated and higher costs as well.

Countermeasure 7. Dynamic horizontal curve speed advisory and control

Equipment needed

- Sensors
  Road-based friction detector
  On-vehicle speed sensor
- Processors
  Calculator for advisory speed
  Decision if conditions are slippery
  On-board decision if control intervention is to be engaged

- Communication Devices
  Transponders
  Wiring or local communications transmitters
  Receivers between friction detector, processors
  Display and transponders
- Displays
  Changeable message sign roadside warning sign with speed advisory
  In-vehicle
    - advisory speed display
    - warning of curve ahead
    - warning to reduce speed
- Controller Units
  Control intervention unit for setting vehicle speed to the advisory speed

Cost

This system is implementable at any of three versions: (1) via roadside display as only a very modest extension beyond the package needed in countermeasure 4, (2) as a combined system with roadside display and an radio frequency (RF) communication to equipped vehicles to effect an on-board warning display, and (3) using roadside, on-board display, and a control intervention on the equipped vehicle, as well. The roadside package noted as version (1) of this system, based upon the commercial price of stand-alone roadside weather stations, is estimated near $40,000. The cost of in-vehicle elements in versions (2) and (3) can be bracketed by (a) Delphi II results which showed $350 to $500 for warning systems to prevent frontal collision, where version (2) of this countermeasure requires only the warning interface, plus a short-range RF receiver—probably costing well under the indicated Delphi II figures, and (b) the Delphi II figure of $750 for automatic braking systems that again seems well above the likely cost of version (3) of this countermeasure since only a decision-logic processor, brake actuator, and RF receiver elements are required.

<u>Countermeasure 8. Longitudinal control for objects in the roadway</u>

Equipment needed

- Sensor for detecting range and range-rate to fixed or slow-moving objects in the lane of travel.
- Control intervention, if driver does not apply brakes, changes direction laterally, and the object does not go away.
- Processor for deciding if warning is needed, if control intervention is required, and for determining the controlled deceleration level.

- Brake actuator to attain selected deceleration.
- Sensor to furnish velocity information to the processor.

Cost

The Delphi II Study estimated the cost of a frontal warning system to be $350 to $500 and the automatic braking capability to be $750 by the year 2008. Assuming that a simple audible warning is approximately costless, once the near-range sensor/processor and decision logic processor are implemented, the Delphi II results might be taken to imply an approximate $800 cost for the combined warning and automatic braking capability by the year 2008. As an additional input, the current price of a VORAD radar system for collision avoidance and obstacle detection applications (such as are currently being installed on the American fleet of Greyhound buses), has been informally estimated by the authors at $1,500 to $2,000 per vehicle in 1993. The total sales volume to which the VORAD cost estimate applies is understood to be less than 3000 units.

Countermeasure 9. Indicators informing drivers of presence of pedestrians at mid-block crosswalks

Equipment needed

- Pedestrian sensors (two piezoelectric or pyroelectric sensors).
- Communication from sensors to sign-controller and from controller to lights.
- Sign-controller that turns a flashing light on for long enough to allow the last pedestrian to cross (perhaps this could be augmented with a device that detects if a pedestrian is in the crosswalk) (one processor and two signs).
- Installation.

Cost

A total cost of $15,400 has been estimated, based upon the sum of $1600 for the sensors, $3800 for processor, signs, and sign-controller, and a total of $10,000 estimated for the installation costs including wiring, under-road and along-road trenching, integration, and other labor-centered costs.

Countermeasures 10 and 11. A system for headway control, based upon a modified cruise control

Equipment needed

- Range and range-rate sensor(s).
- Headway control unit (contains logic and processor for determining velocity commands).
- Cruise control unit that accepts externally generated velocity signals.
- Throttle actuator (may be part of the cruise control unit).
- Driver preferences panel for time-too-short and distance-too-short settings.
- Driver warning system for indicating when situation needs driver intervention.

Cost

This system is expected to be the earliest implementation of all vehicle-autonomous packages listed here and, if market projections are correct, will enjoy price economies deriving from rather high production volume. The Delphi II study predicted a cost of $400 by the year 2004. The authors' understanding is that products will appear on the original equipment manufacturer (OEM) market in model year 1995.

Countermeasure 12. Cooperative warning of the presence of on-coming vehicles

Equipment needed

- Light sensors that can distinguish between headlights and other forms of light.
- Posts with lights in both directions on which the sensors are located.
- Controller and communication link from light sensor to lights.

Cost

This system is defined in two versions. Version (1), characterized by the active illumination of signal lights as a warning to drivers, is estimated to cost on the order of $200 per light standard, in large production volumes, assuming miniaturized photodetection chips and solid state switching of the warning lights. In version (2) a passive system is conceived by which a highly reflective (but not retro-reflective in their function) type of sign would avail recognition by oncoming motorists approaching a curve having limited sight distance at night. The reflective-only version is estimated at $100 per sign.

Countermeasure 13. Warning of the presence of on-coming vehicles

Equipment needed

- Sensors (two loop detectors).
- Communication link from sensor to display-controller.
- Display-controller that keeps display light on from first sensor actuation until last vehicle reaches the display point.
- Installation (conduits, trenching power hook-ups).

Cost

Because this system employs all standard traffic engineering components, its cost estimate reduces to a rather conventional contractor estimation protocol. The total cost at one site is estimated at $20,600 to $24,600, assuming that the loop detectors cost $800 each, the display controller with wiring to the detectors is $3,000, and the installation cost for conduits, trenching, and power hook-up is estimated at $16,000 to $20,000.

Countermeasure 14. Lane-keeping

Equipment needed

- Detectable stripe in the road.
- Car-mounted sensor for detecting the stripe enhancement.
- Processor for: (1) predicting location of the vehicle in relation to the lane and (2) generating warnings and steering commands.
- Warning device to alert driver that the system cannot sufficiently keep the vehicle in the lane.
- Steering actuator that can apply limited steering torques to modulate the path. (These torques might be limited to no more than 2 or 3 ft-lb, measured at the steering wheel.)

Cost

Currently no information is available for estimating the cost of such systems.

Countermeasure 15a & b. Warning drivers on a minor road of the presence of vehicles on a major road (stop signs and yield signs)

Equipment needed

- Sensor for vehicles to the right (one loop detector).
- Sensor for vehicles to the left (one loop detector).

- Communication from the sensors to sign-controller and from sign-controller to sign and installation.
- Sign-controller processor that determines when to illuminate vehicle icons (right and left channels are independent).
- Sign with vehicle icon.
- Optional: indicator of presence of vehicle on the minor road.

Cost

The cost of this system, per intersection approach leg that is to be instrumented, is estimated at $13,100. This cost assumes $800 per detector, $10,000 for the sign controllers, including the sign-controller processor, the communication lines between signs and detectors, and the associated installation costs, power hook-up, etc., and $1500 for each sign bearing an illuminated vehicle icon.

<u>Countermeasure 16. Warning drivers on a major road of the presence of vehicles on a minor road</u>

Equipment needed

- Sensor for presence of vehicle away from the intersection on the minor road (two loop detectors).
- Sensor for a vehicle in the intersection or at the stop signs (two loop detectors).
- Communication links between sensors and sign-controller(s) and lights on the signs installation.
- Sign-controller(s) for lights on signs. (Controls length of time the lights are on. At intersection, light is on as long as there is a vehicle at or in the intersection. Approaching-on-minor-road lights are on for 13 seconds after sensing the latest vehicle pass.)

Cost

The cost of this system is estimated at $22,200 for two approaches and $13,900 for one approach. This cost assumes $800 per individual detector (eight required altogether), $16,000 for communication links between detectors and sign-controllers (with all installation and hook-up costs included) and $3,000 for specialized sign controllers.

Countermeasure 17. Cooperative intersection - four-way stop right-of-way indicator

Equipment needed

- Vehicle presence detector for each approach located at the stop sign (four loop detectors).
- Vehicle presence detector for a vehicle in the intersection (two loop detectors).
- Processor for determining who has the right of way (also takes care of timing even if people go out of order).
- Wiring (communication) to processor and lights and installation.
- Right-of-way lights and stop signs.

Cost

The cost of this system for a four-way intersection is estimated at $17,300. This cost assumes $800 for each of six detectors, $10,000 for the sign controllers (including the sign-controller processor, the communication lines between signs and detectors, and the associated installation costs, power hook-up, etc.), and $2,500 for the right-of-way lights and stop signs.

Countermeasure 18. Approaching vehicle warning for driver making a left-hand turn/warning of vehicle turning left ahead

Equipment needed

1. Approaching vehicle warning for a driver making a left-hand turn:
   - Sensor for observing occurrence of a passing vehicle.
   - Communication of passing observation to the sign-controller (included in the price of signs).
   - A sign-controller for illuminating the left-turn warning when there is not a sufficient gap to make a left turn (light stays on for 6 seconds after the last vehicle passes it even if there was a preceding vehicle that turned the light on) (included in the price of signs).
   - Sensors for observing presence of a left-turning vehicle (two velocity sensors and three deceleration sensors).
   - Sign with lights (display) with processor and controller.
2. Warning that a vehicle ahead is turning left
   - A display for drivers behind the vehicle turning left:
   - Communication of the presence of a left-turning vehicle to the display (the presence sensor would be the one used in part 1) (included in the price of signs).

Cost

The cost of this system is estimated at $17,800 to cover one direction of left-turning traffic. This cost assumes $800 per detector, $10,000 for the sign controllers (including the sign-controller processor, the communication lines between signs and detectors, and the associated installation costs, power hook-up, etc.), and $1,500 for each of the illuminated signs.

THE INFLUENCE OF GENERIC SYSTEM TYPE ON THE DYNAMIC OF PENETRATING THE POPULATION

A great variety of concepts have been postulated for active safety technologies. Among them, we recognize that one generic difference from one type to the next arises from the interdependence of equipment installed either on vehicles or at road sites, in order for the system concept to function. In this regard, we note five such types that are worthy of mention:

1. Autonomous-intelligent vehicle (such that an equipped vehicle provides the desired function to its driver, regardless of the equipment installed on any other vehicle or at any particular road sites).

2. Inter-vehicle communicating (such that an equipped vehicle can provide the desired function to its driver only when operating in the vicinity of another vehicle that is equipped in a complementary manner—affording a wireless exchange of information that enables the countermeasure function.)

3. Autonomous-intelligent road site (by which equipment installed at a road site serves to help all users, in the same manner as conventional intersection traffic signals).

4. Vehicle-roadside communicating (such that an equipped vehicle can provide the desired function to its driver only when operating in the vicinity of roadside equipment by which a wireless exchange of information enables the function.)

5. Inter-vehicle and roadside-communicating (such that an equipped vehicle provides the desired function to its driver only when operating in the vicinity of a road site *and* other vehicle(s) that are equipped to afford a wireless exchange of information that enables the function).

From a simple engineering viewpoint, it is apparent that concepts that incorporate the communication of crucial pieces of information from other vehicles or fixed sites will generally be able to deliver higher levels of crash-avoidance performance than systems that are constrained to operate without such externally generated information. For example, it will be difficult to achieve a robust (i.e., various-collision-mode) level of functionality in a fully autonomous package that must (1) sense the state of a traffic signal, (2) fully appraise the kinematics of approaching vehicles, and (3) deduce collision threats and corrective actions—all by itself. Thus, autonomous systems will tend to target rather isolated crash modes as their delivered function, such as protection from turning left in front of an on-coming vehicle, brake application to avoid a rear-end collision, and so forth. If even a rather simple level of signal-state information were transmitted continuously from the signal controller, however, a substantial hike in functionality would accrue, in concept at least. If even a fairly crude estimate of the location and velocity vector of approaching vehicles were separately quantified and transmitted, a much higher level of system function could result.

Thus, one may surmise that functionality will generally improve, probably in a marked way, when the information available within the host vehicle is augmented with data generated from other vehicles and/or roadside equipment—that is, variables that may be very difficult to characterize autonomously. On the other hand, it is sobering to consider the problem of achieving a population of "other vehicles" and "road sites" that are, indeed, equipped so as to render the cooperative forms of effectiveness that the non-autonomous concepts imply. The significant issue involves the time needed to penetrate a very large national population of either vehicles or candidate road sites—and the "chicken and the egg" syndrome that tends to prevent implementation of equipment that must depend intrinsically upon other elements for its function. Obviously, any person buying the in-vehicle equipment at any point in time must be offered a level of effectiveness that justifies the purchase. Thus, implementation of concepts that require a consumer purchase must satisfy the market dynamic in which the buyer's benefit is more-or-less immediate. The only alternative to satisfying this market axiom may be to mandate the vehicle-borne equipment in, say, all OEM purchases.

The scale of significance of this issue can be portrayed in terms of a "relative effectiveness" that accrues from each type of active safety technology (AST), given the penetration of the system type as well as the inherent dependence of the concept on the state of penetration. Shown in the figure below, each of the five conceptual system types are rated in terms of the relative effectiveness that is appreciated by "each equipped vehicle" and by the "whole population." In the "each vehicle" column, the entered term serves to scale the effectiveness that one individual buyer of such a system would obtain (in the four cases where the concept requires special in-vehicle equipment), given the state of penetration that has accrued. In the "whole population" column, the indicated ratios express the scale of effectiveness by which, say, the national accident experience will be mitigated. The figure shows the following:

1. The type of system that entails autonomous intelligence within individual vehicles will give a relative effectiveness of "1" to each buyer of an equipped vehicle since the package works all by itself as soon as it's driven out of the dealership. In terms of the impact of such a system on the national accident experience, we will see an effect proportioned to the number of such vehicles, N, that are in service, ratioed to the total vehicle population, P, (putting aside, for this illustration, the differences in exposure that may attend the specific set of N vehicles, compared to the population at large).

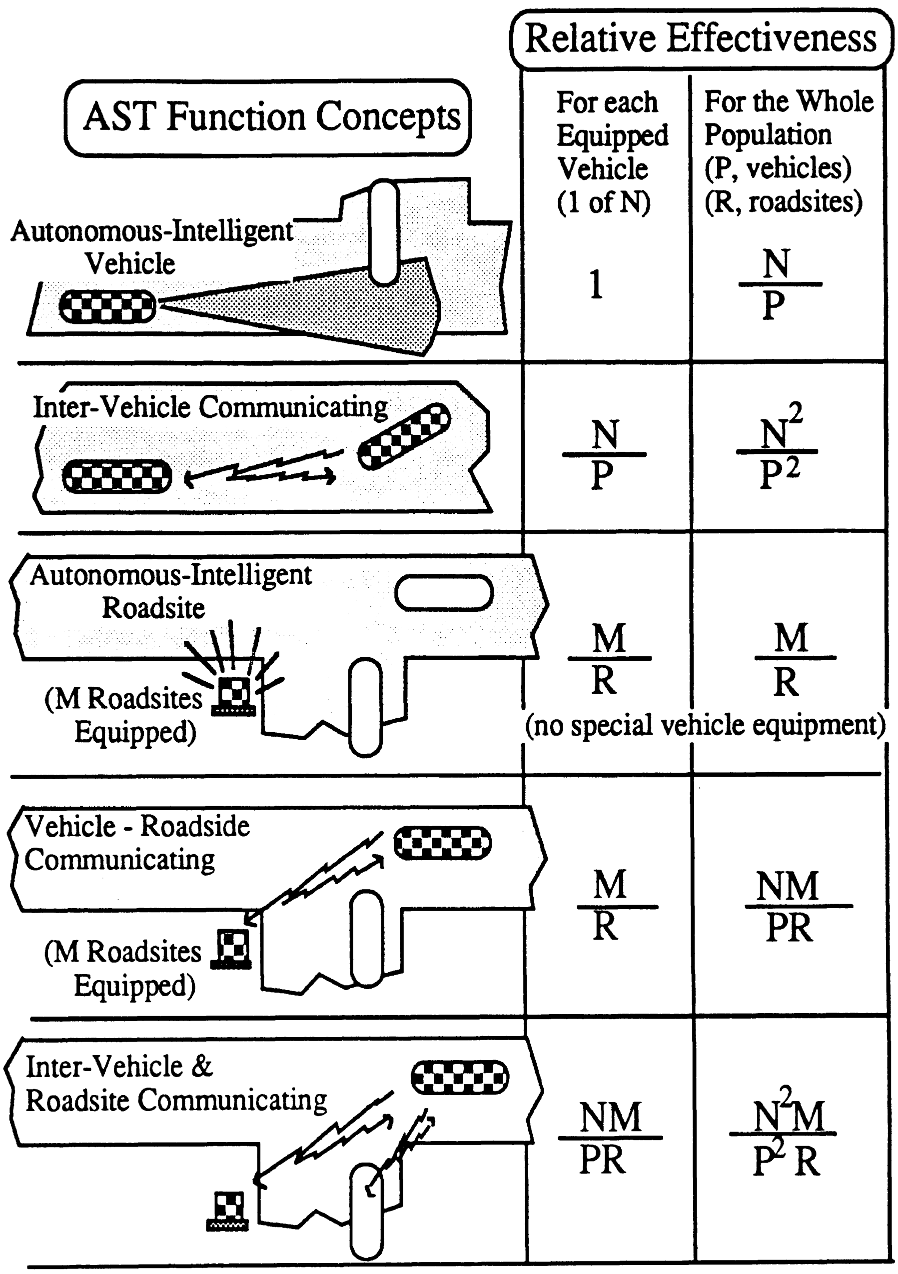


Figure 63. Relative effectiveness for each type of AST.

2. The system based upon *inter-vehicle communication* requires like-equipped vehicles for its operating function. Thus, the driver of each equipped vehicle sees an effectiveness that is scaled to the ratio of N/P—a number that is remarkably low in the early stages of penetration, since P equals approximately 190 million vehicles, nationally. The aggregate effectiveness for the Nation is even worse, resulting in a ratio of N^2/P^2 that reflects the net improbability of equipped vehicles operating in the near proximity of one another, across the Nation.

3. A system involving autonomous intelligence at an individual road site assists all vehicles that pass through the site, thus affording an effectiveness to the average national road user scaled to M/R, where M is the number of equipped road sites, out of a population of R candidate sites. Again, this relative effectiveness expresses average experience and would be higher or lower for individual road users who lived in zones having many or few equipped sites, respectively. The relative effectiveness at the national level is also expressed by M/R since all vehicles would be exposed to the equipment according to that ratio, assuming uniform distribution of traffic (an assumption that is admittedly simplistic given the obvious preference toward deployment at high-accident sites).

4. The system type that involves *vehicle-to-roadside communication* is similar to that of the vehicle-to-vehicle communication case, with the penetrated population of road sites equal to M, out of a population of R candidate sites. The effectiveness for the individual owner of an equipped vehicle is M/R, assuming a uniform distribution of both the vehicle- and road-placed equipment. The national impact is expressed in this case using the product of vehicle and road-site population ratios (NM/PR).

5. Systems that would require communication between vehicles and from vehicles to the roadside equipment are obviously the least likely to deliveri an effective countermeasure, given the penetration dynamics. We see that one individual buyer of the in-vehicle equipment enjoys a relative effectiveness of only NM/PR, while the national impact, again assuming gaussian distributions just for the sake of simplicity of the illustration, is scaled according to the dismal ratio N^2M/P^2R.

Moreover, we see a dilemma in the conceptualization of active safety countermeasures for avoiding various modes of collision. Namely, the technical considerations are likely to argue for systems having inter-vehicular and/or vehicle-to-roadside communications, but the penetration dynamics argue for autonomous systems. Clearly, Federal safety policy needs to be based upon careful examination of alternatives, recognizing this tradeoff and rationalizing research and development priorities, accordingly.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS CONCERNING POTENTIAL SAFETY APPLICATIONS OF ADVANCED TECHNOLOGY

CONCLUDING REMARKS AND CONCLUSIONS

Statistical analysis based upon accident types

This research used a large national accident data set to develop an accident data typology that classified crashes in terms of collision avoidance-related factors.

The collision typology, which emphasizes pre-crash movements and intents of vehicles, identified targets of opportunity for achieving safety benefits with advanced technology. Based on the typology, six collision types were found to account for 68 percent of all single-and two-vehicle crashes. These are: run-off-the-road, rear-end, head-on, crossing paths at intersections where both vehicles were going straight, left turn collisions where one vehicle turns left across the path of another, and single-vehicle collisions with a pedestrian, cyclist, or animal. Countermeasures addressing these types of collisions would have the potential to achieve large safety benefits. The accident data files were further used to identify the roadway, driver, and environmental factors associated with each specific crash type. These associated factors included roadway curvature, intersection traffic control, impaired driver, excessive speed, light conditions, and pavement conditions. The associated factors, in turn, were key in designing and specifying the collision avoidance systems or countermeasures.

A main conclusion derived from this work is that there are two generic types of countermeasure systems, namely, crosscutting and accident-type specific. As the name implies, the crosscutting countermeasures apply to many different accident types. The accident data factors associated with these countermeasures are driver impairment, dark and unlit situations, and slippery or icy roads. Countermeasures that are accident-type specific are related to providing additional information and perhaps control interventions that address pertinent features that are inherent to the crash type. For example, for crashes involving running off the road, a countermeasure system is based upon detecting the road edge and warning the driver when the vehicle approaches the road edge, and then applying the brakes if the vehicle crosses the road edge and leaves the road.

Conclusion

As indicated in the above paragraph and the material presented in chapters 2 and 6, the development of an accident typology and an investigation of the factors associated with each type of crash was key to the process of creating and inventing countermeasure systems in this study.

Functional requirements for countermeasure systems

A major challenge of this project was the creation and invention of the countermeasure systems described in chapter 4. Even though the factors associated with various crash types provide a good starting point for defining countermeasure systems, they do not tell the researcher what the countermeasure system should be. In this study, the researchers used their intuition to develop descriptions of countermeasure systems that appeared to have potential for mitigating the circumstances associated with various types of crashes.

In hindsight, we see the development of countermeasure systems as an iterative process. In this study, an iterative process was started and partially completed, not by design, but because it was the only way the researchers could find to proceed. They needed to assert that certain countermeasure systems might be useful and then proceed to evaluate them.

As a result of this process, the results and findings of this study indicate that certain countermeasures are expected to have greater potential benefits than others. In a sense, the functional requirements are one thing and the effectiveness of the countermeasure is another. One could write very good functional requirements for a countermeasure that only addresses a relatively small number of accidents. From the perspective of improving the overall safety of the roadway transportation system, such functional requirements would be poor because they do not represent a powerful concept for eliminating crashes.

Conclusion

The significant functional requirements derived from this study pertain to the most beneficial countermeasure systems, namely headway control systems, lane departure protection, lane-keeping, night vision enhancement, longitudinal control for avoiding objects in the road, and impaired driver warning.

Methodology for evaluating countermeasures

The evaluation of the countermeasures consisted of estimating the number and severity of accidents in the cases recorded in the CARDfile sample that would occur if the countermeasure was in effect and comparing them to the original number and severity of accidents in the file (i.e., without the countermeasure). The severity classes constituted property damage and minor injury, incapacitating injury, and fatal. A monetary cost for each severity class for each of the six accident types was calculated based on costs of vehicle crashes published by the Federal Highway Administration. The percent change in the total number of accidents and in the total accident cost were used as the figures of merit in the evaluation.

The set of crashes for each CM was identified, defined by accident type and associated factor that the countermeasure was designed to address. It was assumed that if the countermeasure had been in effect, some of the crashes would not have occurred and the severity of those that did occur would be different from that originally observed. Those categories of accidents not addressed by a particular countermeasure would occur exactly as they did before.

Three methods for estimating the number and severity of crashes with a countermeasure in effect were developed in this research. These are the prorated distribution method, the physical analysis method, and the generic method, as described below:

1. Prorated accident distribution - This method was used in crosscutting countermeasures that are applicable to all six crash types. These include vision enhancement, impaired driver warning, and low-friction warning. It was assumed that the number of accidents from the set that would not have occurred with the countermeasure in place would be proportional to the portion of accidents in the set that are conceptually addressed by the countermeasure. It was further assumed that the severity of the accidents that did occur would be distributed according to the originally-observed distribution of the set of accidents, defined by all the same associated factors, except the one addressed by the countermeasure.

2. Physical Analysis - The physical analysis method is applicable to crash-type-specific countermeasures where the motions of the vehicle in the crash situation and in the countermeasure action can be generally described in physical terms. This method uses the relationships between distance, time, speed, and acceleration pertaining to the crash types and their countermeasure systems. Countermeasures that involved braking, such as headway control and longitudinal control for objects

in the road and those that involved steering and braking such as lane-edge detection, and on-coming vehicle warning were evaluated by this method.

This approach assumes that the countermeasure has some effect in every case and thus yields extraordinarily large benefits. In reality, there would be some inefficiency associated with the countermeasure that would lower those benefits. This research did not investigate experimental means for assessing efficiencies. However, results are presented for various levels of efficiency, thereby recognizing that efficiencies of 100 percent are not realistic.

3. Generic method - This method was developed when neither the physical analysis method nor the prorated accident distribution method were feasible. This was the case whenever there were unknown associated factors or other unknowns in the set of accidents. This method was used in the case of the pedestrian mid-block crossing, and all the intersection countermeasures.

In such cases, the number of accidents in each severity class is reduced by Nq(Nq/Nt)/Nt, where Nq is the number of cases conceptually addressed by the countermeasure and Nt is the total number of cases in the severity class. The quantity (Nq/Nt) represents a measure of effectiveness of the countermeasure based upon the idea that the effectiveness of the countermeasure is in proportion to the number of crashes in question divided by the total number of crashes of that type. The fraction of cases reduced is obtained by dividing by the total number of crashes in the severity class.

The generic method is much less labor-intensive that either the prorated distribution or physical analysis methods. Countermeasure benefits calculated by the physical analysis method and the generic method were similar enough to support use of the generic method as a quick and easy "first-cut" assessment of the potential safety benefits of a countermeasure.

Conclusion

Countermeasure safety benefit potential can be meaningfully estimated from large-scale accident data sets.

The method of evaluation depends on the type of countermeasure and on the availability of information in the data about the associated factors relevant to that countermeasure. Three methods were developed in this research. They are detailed in chapter 6.

The generic method of evaluation provides a reasonable, quick, and easy "first-cut" assessment of the safety benefit potential of a countermeasure.

Potential safety benefits

Highest payoff

Examining the evaluations of benefits of the set of countermeasures explored in this research indicates that the largest safety benefits could be realized by headway control systems, lane-edge detection, lane-keeping, night vision enhancement, driver impairment warning, and longitudinal control to avoid objects in the road.

The universal application of headway control countermeasures, that targets rear-end crashes is estimated to have a potential of reducing the total number of accidents by about 13.5 percent and the accident costs by about 7.2 percent. Lane-edge detection systems, which target run-off-the road crashes, are estimated to reduce the number of accidents by about 9.5 percent and the accident cost by 11.7%. It should be noted that these countermeasures were evaluated using the physical analysis method that tends to give large benefits because it assumes an efficiency of 1. However, even at an efficiency level of .5, the headway control countermeasure has a potential of reducing the number of accidents by 6.7 percent and the accident cost by 3.6 percent, and the lane-edge detection system has a potential of reducing the number of accidents by 4.8 percent and the cost by 5.8 percent.

Lane-keeping countermeasures, which address run-off-the-road and head-on crashes, were estimated to reduce the total number of crashes by 12.3 percent and the cost by 7.3 percent. The estimation method was the generic method that already includes a measure of efficiency.

Night vision enhancement systems that address all types of crashes are estimated to have a potential of reducing the total number of accidents by 3.6 percent and the cost of accidents by 7.3 percent.

The evaluation of the impaired driver warning indicates that this countermeasure can reduce the number of crashes by 1.2 percent and the cost by 9.9 percent. The generic evaluation yielded potential reductions of 1.3 percent for the number of crashes and 5.7 percent for the costs. The large cost reduction is due to the reduction in fatal accidents qualifies this countermeasure as one with a potentially high payoff.

The countermeasure that provides longitudinal control avoiding objects in the road was estimated to have a potential of reducing the total number of accidents by 3.5 percent and the total costs by 3.4 percent using the physical analysis method. The generic method gave somewhat higher estimates of 5.0 percent for accident reduction and 5.1 percent for the cost reduction. It should be noted that this evaluation considered only single-vehicle accidents with pedestrians, cyclists, and animals and did not consider crashes with other stationary objects in the roadway. Therefore, since this countermeasure may also be able to detect such objects, the higher benefit potential estimates may be reasonable.

Conclusion

Countermeasures identified by this research as having the most potential for safety benefits are:

- Headway control
- Lane-edge detection
- Lane-keeping
- Night vision enhancement
- Impaired driver warning
- Longitudinal control for avoiding objects in the road

Medium payoff

The safety benefit potential of low-friction detection and cooperative intersections are somewhat lower than those of the countermeasures enumerated above.

The low-friction detection system, another crosscutting countermeasure, was estimated to have a potential of reducing the total number of accidents by 4 percent and the cost by 3.2 percent by the prorated distribution method and by 1.7 percent and 1.2 percent, respectively, by the generic method. This countermeasure would prevent many of the low-severity accidents, or the "fender-benders" associated with low-friction conditions, which do not carry a large monetary cost.

The three intersection countermeasures were evaluated as a set because the data did not contain information about the type of traffic control at signed intersections. These countermeasures consisted of roadside systems at intersections controlled by stop and yield signs. As a set, their potential to reduce accidents and costs was evaluated at 2.2 percent and 2.8 percent, respectively.

Conclusion

Countermeasures identified as having medium potential for safety benefits are:

Low-friction detection systems

Signed-intersection countermeasures

Spot improvements

The universal application of the following set of countermeasures does not appear to have a particularly large potential for accident reduction: horizontal curve speed advisory, pedestrian detection at mid-block crossing, on-coming vehicle warning, and left-turning vehicle warning. In each case, the potential for accident and cost reduction was at or below 1 percent. These countermeasures, do have the potential to be beneficial at specific problem locations.

Conclusion

The following countermeasures have potential as spot improvements at problem locations:

Horizontal curve speed advisory
Pedestrian detection at mid-block crossings
On-coming vehicle warning
Left-turn warning

Pertinent technology

An extensive discussion of technological options for creating countermeasure systems was presented in chapter 5, indicating that the key enabling module of most systems is some form of sensing. The results of the safety benefit analysis are especially pertinent to the issue of technology, and particularly to sensing technology, insofar as the highest safety payoffs appear to align with countermeasures that were conceived as systems installed within vehicles. As shown in the table below, the top-ranked countermeasures all involve vehicle-autonomous systems and all require remote sensing of one type or another. The percentage of reductions in total accident cost shown in the table is drawn from the so-called "generic" method of cost computation.

Table 49. Ranking of countermeasures by benefit.

Rank No. by Benefit	Countermeasure Function	Type of Countermeasure	% Reduction, Total Accident Cost
1	CM10 and 11, headway control	veh-autonom.	7.6
2	CM5, lane-edge detection	veh-autonom.	7.5
3	CM6, lane detection with previews	veh-autonom.	7.5
4	CM14, lane-keeping	veh-autonom.	7.3
5	CM1, night vision	veh-autonom.	6.7
6	CM2, driver impairment warning	veh-autonom.	5.7
7	CM8, longitudinal control - objects	veh-autonom.	5.1
8	CM15-17, intersection crossing	roadside	2.8
9	CM3, friction/ice detection	veh-autonom.	1.2
10	CM4, friction/ice detection	roadside	1.2
11	CM18, intersection left turn	roadside	1.1
12	CM12 & 13, warning of on-coming	roadside	0.8
13	CM7, horizontal curve advisory	roadside	0.6
14	CM9, pedestrian crosswalk	roadside	0.2

Combining these data with the observations in chapter 5 associated with all of the top-ranked countermeasures indicates that the key technological thrust that would have the greatest pertinence to accident prevention involves remote sensing of both the active point-measurement type and the passive emission-imaging type. The active-point type sensors would address the systems having rank numbers of 1 and 7. Both of these systems must detect vehicular or human/animal presence both in range and range-rate forms of processing. Systems ranked at levels 2, 3, and 4 (all of which call for sensing of lane layout relative to the vehicle) require imaging of lane edges, presumably (but not necessarily) by means of passive sensors. The system ranking as number 5, night vision enhancement, is generally acknowledged as requiring passive imaging of the roadway scene. The driver impairment warning system, ranked as number 6, can be implemented using direct-sensing devices such as steering or throttle displacement transducers, but this function has also been conceived as derivable from passive imaging of the lane-following behavior of the driver, using the same sensors as employed for lane-detection (rank numbers 2, 3, and 4).

Moreover, these top-ranked concepts will put the premium on the sensor itself and the associated processing by which the complex sensory output signals are reduced to high-order recognition data from which control decisions can be made. Depending upon the application, it is also likely that rather sophisticated forms of artificial intelligence will be needed to effect fully satisfactory functions.

Conclusion

This research indicates that the key technological thrust that would have the greatest pertinence to accident prevention involves remote sensing of both the active point measurement and the passive imaging types.

Costs

Estimates of the delivered cost of most of the countermeasures were attempted during this study. In general, the systems that were conceived as autonomous to the vehicle were estimated by means of a a delphi survey and do not reflect any rigorous process of reduction from a specific design to component-costing, and therefore, to product-pricing. While costs ranging from $350 to $2000 were indicated across the various vehicle-autonomous systems, it is widely recognized within the auto industry that options priced above $1000 are very hard to sell and thus would not penetrate the population rapidly.

At the same time, it is recognized that the field of automotive electronics is undergoing dramatic change with each new model year and that this change will undoubtedly make safety enhancements more economical and more extendible to other on-board systems. As these innovations tend to include more subsystems under electronic control (including the engine, transmission, brake and traction-control systems, suspension, and steering systems) and as the trend expands toward greater use of multiplexing from a commonly accessible bus, the in-vehicle foundation becomes more and more attractive for addition of new intelligent functions such as the active safety countermeasures considered here.

Concerning roadside-installed systems, it must be recognized that the warrants for deployment would be established a site at a time, just as in the current practices of traffic and safety enhancement by State and local highway agencies. When we look at the various roadside countermeasures (ranked 8, and 10 through 14 in table 49) we note that all of the cost estimates are in the vicinity of $20,000 per site. This cost level, while likely to be seen as relatively high given typical State and local budgets for site safety improvements, are not out of line with the $50K to $100K costs of modern intersection signal installations.

Finally, it should be emphasized that all costing figures estimated in this study are preliminary in nature and very likely to change as more detailed engineering analyses are increasingly undertaken by government and industrial developers of countermeasure systems. While the estimates are thought to be useful as first-order projections, the reader is cautioned to avoid making strong distinctions between systems on the basis of the presented costs.

Conclusion

Costs of advanced countermeasure systems depend on investments in research and development, economies within a family of synergistic products, marketing strategies, and production volume, all of which are difficult to estimate with any level of confidence for a system in the conceptual state.

OBSERVATIONS AND RECOMMENDATIONS

On associations found in the accident data

Associations found in large-scale accident data point out where countermeasures could be effective. On the other hand, accident investigators seek more detailed physical information than that existing in the mass accident data. Accident investigators attempt to pin down the causes of crashes in terms of very detailed information. Undoubtedly, this type of detailed information would be useful in evaluating and creating countermeasure systems. There appears to be a dilemma in that mass data are needed to assess the potential safety benefits of a countermeasure system and detailed information is needed to plan and test carefully targeted countermeasure systems. The resolution to the dilemma could be that both types of data are needed. As vehicles become more instrumented, perhaps provisions will be made to obtain objective accident investigation like information on a mass scale. The NHTSA iniative on quantitative characterization of the vehicle motion environment (VME) will generate useful insights into the details of everyday collision avoidance behavior. In the mean time, one can work towards developing pertinent crash scenarios for prevalent crash types and using simulators to study these scenarios.

Recommendation

Use the generic method to get a first-order estimate of the potential of a countermeasure system developed for addressing an associated factor pertaining to a specific crash type. Then use analyses based on vehicle maneuvering dynamics and human reaction capabilities to refine the first-order estimates. Back this up with simulator studies based upon scenes and scenarios that attempt to include all of the significant factors associated with particular crash types.

On functional requirements

Our understanding of the role of functional requirements developed as the project progressed. We can look back and conclude that the following ideas may be helpful in developing functional requirements in future studies.

We recognize that there is no single "right way" for undertaking the hard thinking that leads to sound functional goals that will ultimately mesh with all of the constraints of the problem. Nevertheless we observe that it is useful to pursue the definition of functional goals by considering each targeted crash problem from three points of view. The three points of view look at the countermeasure in terms of (1) its input-output relationship, (2) the action it takes, and (3) the system concept that it embodies.

Using the first point of view, functional goals are stated in terms of *input-output* relationships that, in a sense, define the countermeasure. The inputs are roadway constraints, velocities, dimensions, etc. of the crash-threat setting that are measurable and can be used as the raw information upon which a countermeasure may operate. The outputs are the changes in the conflict variables (motion vector headings, magnitudes, or phasing between multiple vehicles) that would desirably prevail if the countermeasure function was implemented by a physical system, and therefore, the driver.

By a second point of view, we note that a function can be looked upon as the action itself, for which a thing exists. Using this focus, one can build an "action hierarchy" running from the broadest conceptual statements (such as "prevent the host vehicle's path from closing upon an intruder from the side," "prevent the host vehicle from intruding at a stop-signed intersection") to intermediate actions generally dealing with kinematics (such as "pass by to the right," "pass by to the left," "restrain the stopped vehicle from initiating motion," "reduce speed to effect a space gap in future time," etc.) to descriptions of elemental control actions (such as "apply service brakes," "downshift transmission," "apply differential braking to achieve a yaw moment," "present a direction-specific warning to driver", etc.).

A third approach to stating the functional goals is based upon specific system concepts for sharing space and for negotiating that space without a crash. The highway community has certain "system concepts," of course, by which it explicitly generates gaps (using basic traffic signals, protected left-turn signaling, and grade-separated roadways) or enables drivers to seek and find their own gaps (assisted by stop and yield signs, centerline striping and so on, given the right-of-way rules). These system concepts, while embodying rather straightforward functional goals, have been reduced to codified application by traffic engineers. For active safety-type countermeasures, one should consolidate the functional ideas coming from input-output and action-centered deliberations, discussed above, into system concepts that either "make" or "find" gaps in traffic using new technology. The system concept, at this stage, does not define the technology from which it might be built, but rather defines the countermeasure function in terms that will support a meaningful statement of its goal.

Every attempt should be made to identify system concepts and develop their functional goals so as to address substantial numbers of crashes. Nevertheless, our experience is that as one more and more carefully defines the causes and influential conditions for a target set of crashes, the portion that is likely to be covered by a given countermeasure may tend to dwindle. Thus, we seek robust system concepts at the same time as we consider the practicality that each could somehow be implemented.

Recommendation

Ideally functional requirements for a countermeasure system should be stated in a manner that includes at least the following three items: (1) its input-output relationship, (2) the action that it takes, and (3) the system concept that it embodies.

On high payoff countermeasures

The countermeasures identified by this research as having the most potential for achieving safety benefits need remote sensing capabilities on-board vehicles. The choice is not clear between microwave radar, infrared, and optical technologies. For short-range sensing, ultrasonics are also a candidate.

Recommendation

Studies of autonomous countermeasure systems on-board vehicles should, in the near term, emphasize sensors and smart sensors that emulate the driver's recognition/perception function.

On infrastructure-related countermeasures

New types of infrastructure-related countermeasures require vehicle presence detectors, and perhaps vehicle speed and acceleration detectors, as well as real-time variable-message signs. The highway engineering community has emphasized safety for many years. Roads are built very conservatively with respect to safety. Road design policies tend to provide alert drivers with adequate time to react to changing situations and adequate space in which to maneuver as long as drivers observe driving rules and road designers apply existing policies. We did not see a pressing need to revise road design policies to better accommodate the safe operation of passenger cars.

Recommendation

Develop prototypical countermeasure systems using vehicle presence detectors and real-time variable-message signs and test them with controls and instrumentation as needed to get field evaluations.

On the focus of future projects

This project examined nearly 20 countermeasure concepts and systems. In the course of the work it became apparent that while this number was manageable for an overview project, it was overwhelming if the concepts were to be taken further within the context of a single research study.

Recommendation

Focus future projects into individual crash-specific areas and into individual crosscutting subjects (driver impairment, vision enhancement, and slippery roads).

On data needs

The evaluation of crash-specific countermeasures beyond the first-order estimates relies on analysis of human reaction capabilities and the maneuvering dynamics of the vehicle. For these analyses, initial traveling speed is vital. The distance consumed while the driver is reacting to a problematic situation depends upon the product of the driver's reaction time with the initial traveling speed. The space taken or the deceleration needed in braking maneuvers depends upon the square of the initial traveling speed. The acceleration needed or used in a turning or swerving maneuver depends upon the square of the traveling speed, also. However, this information is not readily available in most accident data files. Even on those that supposedly carry this information, it is often missing.

In addition, the speed at impact provides an important indicator of when and how aggressively the driver reacted to a problematic situation. Clearly, the absolute speed of the vehicle at impact would be a better quantity for use in investigating pre-crash, collision-avoidance safety than the change in velocity, "delta V" used for crash-worthiness studies. It also appears that velocity at impact would be easier to define and measure than delta V. Examination of accident data sources indicates that delta V information has been gathered in relatively few cases and that the speed of impact is even less frequently known.

It is probably too much to expect that speed-of-impact information will be gathered until there is on-board instrumentation for doing it. However, it appears that traveling speed information could be assessed and recorded with much greater frequency than it is now. Again, the Vehicle Motion Environment Measurement Program would provide an authoritative source of such speed data, in conjunction with position information.

Recommendation

Collect vehicle speed information when collecting data for accident files. If at all possible, estimates of initial traveling speed should be incorporated in mass accident data files. And if speed at impact is available, that information should be recorded and saved also.

On the need for human factors studies

The best system in theory is no good if people cannot or will not use it. Many countermeasure systems depend upon communicating additional information to the driver. The form of this communication of information should be such that the driver can react faster if that information is present. Drivers are known to slow down to read signs, make turns, and to look closely at the passing scene. The presence of countermeasure systems should not constitute a driving hazard.

As countermeasure systems become defined in hardware and software, the influences of human performance and interaction on their effectiveness will need to be assessed.

Recommendation

Variable-message and real-time displays both in the vehicle and at the roadside should be evaluated in both field studies and simulator experiments for determining their compatibility with human factors constraints.

On a theory and science of driving

A model of the driving process is needed to provide a foundation to use in developing and evaluating countermeasure systems. The theory underlying the model would provide the basis for a generalized rationale supporting countermeasure systems that aid drivers in selecting traveling speed and performing the observation and control functions associated with crash prevention and avoidance activities. The science represented in the model would provide a basis for evaluating proposed and prototype countermeasure systems in an objective manner that challenged the underlying logic of these systems.

Recommendation

Research into driver control of vehicles on roadways should be enhanced by the development of a theory and science of driving as needed to model the driver-vehicle-roadway system from a perspective emphasizing the control system and informational aspects of the driving process.

On sensor range, false alarms, enhanced situation awareness, and the co-driver

A pertinent observation from the experience of inventing countermeasure systems is that sensor range needs to be far enough to provide enough reaction time for the driver or the control unit plus enough space for maneuvering the vehicle to avoid crashes. This range, along with the traveling speed of the vehicle, determines an amount of time available for responding to problematic situations that may develop in the course of driving.

However, the amount of space and time covered by the sensor also determines the likelihood of a false alarm being issued by a countermeasure system. Drivers that are alert may require less space and time to perform avoidance actions. If the countermeasure system is tuned to a poor driver, it may produce many false alarms for an alert driver. On the other hand, if the system is tuned to an alert driver, it may fail to issue needed warnings for drivers with long reaction times. A similar discussion involving false alarms and missed threats can be applied to vehicle capabilities and environmental conditions. It appears that the output of the sensor needs to be processed in a manner that pertains to the current driver-vehicle-roadway-environmental conditions existing at each moment during travel.

The safety management concept outlined in chapter 4 and the ideas applied to the design of aircraft cockpits under the label "enhanced situation awareness" appear to address the issue of how to coordinate all of the various safety-related countermeasures into a co-driver system.

Recommendation

Research into driver control of vehicles on roadways should include studies aimed at developing a co-driver concept for safety management involving enhanced situation awareness pertinent to the characteristics of each particular driver-vehicle system at each moment during travel.

APPENDIX A. DEVELOPMENT OF THE GENERIC EFFECTIVENESS ESTIMATION METHOD

- Let Nt be the total number of crashes of the type selected for consideration. The countermeasure under consideration addresses some subset of these cases.
- Let Nq be the number of cases that may be affected by the countermeasure.
- Then (Nt-Nq) is the number of cases that are not addressed by the countermeasure and, therefore, will not be affected by the countermeasure.
- It is assumed that the countermeasure will have enough effect on some of the Nq cases so that a crash does not occur.
- It is also assumed that for the remaining Nq cases, the effect of the countermeasure will not be enough to avoid a crash (but may cause crash severities to reduce).
- The portion of the Nq cases that still result in a crash, even with the countermeasure, is assumed to be proportional to the ratio of the number of cases not affected by the countermeasure to the total number of original crashes or (Nt-Nq)/Nt.

Thus, the number of crashes (with the countermeasure) is:

$$(Nt-Nq) + Nq(Nt-Nq)/Nt = Nt - Nq^2/Nt = Nt(1-Nq^2/Nt^2)$$

Therefore, the fraction, Nq^2/Nt^2, represents the factor by which the countermeasure will reduce the rate of occurence of accidents of the selected type.

Table 50. Demonstration of reduction fraction development in generic method.

Nt	Nq	not Nq	Nq(not Nq/Nt)	Crashes with CM	Crashes Saved	Nq*(Nq/Nt) √	Reduction Fraction
100	100	0	0	0	100	100	1.00
100	90	10	9	19	81	81	.81
100	80	20	16	36	64	64	.64
100	70	30	21	51	49	49	.49
100	60	40	24	64	36	36	.36
100	50	50	25	75	25	25	.25
100	40	60	24	84	16	16	.16
100	30	70	21	91	9	9	.09
100	20	80	16	96	4	4	.04
100	10	90	9	99	1	1	.01
100	0	100	0	100	0	0	.00

Table 50 demonstrates steps in the development of the generic evaluation method. Here the total number of crashes is 100 as shown in the Nt column. Column Nq shows the number of crashes that are addressed by the countermeasure and ranges from 0 to 100. The third column, not Nq, shows the corresponding number of crashes upon which the countermeasure has no effect. The number of crashes from the set, Nq, that still occur, even after the countermeasure is deployed, is shown in the fourth column. The fifth column shows the total number of crashes from the set Nt that occur with the countermeasure in effect. These values are a total of the "not Nq" crashes and those from Nq that still occur. The number of crashes that did not occur because of the countermeasure is shown in the column labeled "crashes saved" and is the difference between columns one and five. The second to last column is a checking column and the last column shows the reduction fraction (Nq/Nt)2.

Note, that in cases where Nq is a large portion of Nt, or where the countermeasure addresses a large portion of the crashes the reduction fraction is large, but decreases rapidly as Nq decreases.

APPENDIX B.

Table 51. Impaired driver countermeasure — run-off-the-road crashes.

All alcohol crashes prorated to no alcohol condition
Ratio of no alcohol/all crashes = .743

					Post CM	With countermeasure		
	Total	PDO/Inj C	Injury	Fatal	Total	PDO/Inj C	Injury	Fatal
Alcohol/drugs only	3259	1918	1283	58	2421	1787	612	18
Distribution of none of the above	1.00	.74	.25	.01				
Alcohol and dark only	3830	2182	1537	111	2846	2082	740	31
Distribution of dark only	1.00	.73	.26	.01				
Alcohol, snow/ice, no speed	116	87	29	0	86	74	12	0
Distribution of snow/ice, no speed	1.00	.86	.14	.00				
Alcohol, snow/ice, speed	73	48	24	1	54	44	9	0
Distribution of snow/ice, speed	1.00	.82	.17	.00				
Alcohol, wet, speed	246	162	77	7	183	142	40	1
Distribution of wet, speed	1.00	.78	.22	.00				
Alcohol, dark, snow/ice, no speed	183	131	49	3	136	119	17	0
Distribution of dark, snow/ice, no speed	1.00	.88	.12	.00				
Alcohol, dark, snow/ice, speed	158	118	40	0	117	100	18	0
Distribution of dark, snow/ice, speed	1.00	.85	.15	.00				
Alcohol, dark, wet, speed	302	172	121	9	224	169	51	1
Distribution of dark, wet, speed	1.00	.75	.23	.01				
Total	8167	4818	3160	189	6068	4517	1499	52

	PDO/Inj C	Injury	Fatal
Crashes by severity	4,818	3,160	189
Crashes by severity with countermeasure	4,517	1,499	51
Difference	301	1,661	138

Table 52. Impaired driver countermeasure — vehicle strikes pedestrian/cyclist/animal.

All alcohol crashes prorated to no alcohol condition
Ratio of no alcohol/all crashes = .974

	Total	PDO/Inj C	Injury	Fatal	Post CM Total	With countermeasure PDO/Inj C	Injury	Fatal
Alcohol/drugs only	146	42	88	16	142	81	59	2
Distribution of none of the above	1.00	.57	.41	.02				
Alcohol and dark only	124	75	40	9	121	101	9	1
Distribution of dark only	1.00	.90	.08	.01				
Alcohol, snow/ice	6	3	2	1	6	4	2	0
Distribution of snow/ice	1.00	.60	.37	.02				
Alcohol, dark, snow/ice	8	3	5	0	8	8	0	0
Distribution of dark, snow/ice	1.00	.97	.02	.01				
Total	284	123	135	26	277	194	70	3

	PDO/Inj C	Injury	Fatal
Crashes by severity	123	135	26
Crashes by severity with countermeasure	194	70	3
Difference	-71	65	23

Table 53. Impaired driver countermeasure — crossing paths.

All alcohol crashes prorated to no alcohol condition
Ratio of non-alcohol/all crashes = .949

					Post CM	With countermeasure		
	Total	PDO/Inj C	Injury	Fatal	Total	PDO/Inj C	Injury	Fatal
Alcohol/drugs only	134	89	41	4	127	106	21	0
Distribution of none of the above	1.00	.84	.16	.00				
Alcohol and dark only	25	18	6	1	24	20	4	0
Distribution of dark only	1.00	.82	.17	.01				
Alcohol, snow/ice, only	6	5	1	0	6	6	0	0
Distribution of snow/ice only	1.00	.94	.06	0				
Alcohol, signalized only	379	234	141	4	360	289	69	1
Distribution of signalized only	1.00	.80	.19	.00				
Alcohol, signed only	340	223	112	5	323	263	59	1
Distribution of signed only	1.00	.81	.18	.00				
Alcohol, dark, signalized only	106	68	37	1	101	78	23	0
Distribution of dark, signalized only	1.00	.77	.22	.00				
Alcohol, dark, signed only	110	65	38	7	104	77	24	2
Distribution of dark, signed only	1.00	.74	.23	.02				
Alcohol, signalized snow/ice only	17	13	4	0	16	15	1	0
Distribution of signalized, snow/ice only	1.00	.93	.07	0				
Alcohol, signed snow/ice only	10	7	3	0	9	8	1	0
Distribution of signed, snow/ice only	1.00	.93	.07	.00				
Alcohol, dark, snow/ice	12	6	6	0	11	7	1	0
Distribution of dark, snow/ice	1.00	.89	.11	0				
Total	1139	728	389	22	1081	869	202	4

	PDO/Inj C	Injury	Fatal
Crashes by severity	728	389	22
Crashes by severity with countermeasure	869	202	4
Difference	-141	187	18

Table 54. Impaired driver countermeasure — left turns.

All alcohol crashes prorated to no alcohol condition
Ratio of non-alcohol/all crashes = .944

	Total	PDO/Inj C	Injury	Fatal	Post CM Total	With countermeasure PDO/Inj C	Injury	Fatal
Alcohol/drugs only	208	125	79	4	196	150	46	0
Distribution of none of the above	1.00	.76	.23	.00				
Alcohol and dark only	77	42	34	1	73	54	18	1
Distribution of dark only	1.00	.74	.24	.02				
Alcohol, snow/ice, only	4	3	1	0	4	4	0	0
Distribution of snow/ice only	1.00	.89	.10	0				
Alcohol, signalized only	222	150	69	3	210	168	41	0
Distribution of signalized only	1.00	.80	.20	.00				
Alcohol, signed only	41	28	12	1	39	32	7	0
Distribution of signed only	1.00	.82	.17	.00				
Alcohol, dark, signalized only	58	33	25	0	55	45	10	0
Distribution of dark, signalized only	1.00	.82	.18	.01				
Alcohol, dark, signed only	14	5	9	0	13	10	3	0
Distribution of dark, signed only	1.00	.77	.23	0				
Alcohol, signalized snow/ice only	7	5	2	0	7	6	1	0
Distribution of signalized, snow/ice only	1.00	.87	.13	0				
Alcohol, signed snow/ice only	1	1	0	0	1	1	0	0
Distribution of signed, snow/ice only	1.00	.79	.21	0				
Alcohol, dark, snow/ice	4	3	1	0	4	4	0	0
Distribution of dark, snow/ice	1.00	.94	.06	0				
Total	636	395	232	9	600	473	126	1

	PDO/Inj C	Injury	Fatal
Crashes by severity	395	232	9
Crashes by severity with countermeasure	473	126	1
Difference	-78	106	8

Table 55. Impaired driver countermeasure — rear-end crashes.

All alcohol crashes prorated to no alcohol condition
Ratio of non-alcohol crashes/all crashes = .933

					Post CM	With countermeasure		
	Total	PDO/Inj C	Injury	Fatal	Total	PDO/Inj C	Injury	Fatal
Alcohol/drugs only	1676	1301	372	3	1564	1416	147	1
Distribution of none of the above	1.00	.91	.09	.00				
Alcohol and dark only	678	469	199	10	633	557	75	1
Distribution of dark only	1.00	.88	.12	.00				
Alcohol, snow/ice, no speed	54	42	12	0	50	48	2	0
Distribution of snow/ice, no speed	1.00	.96	.04	0				
Alcohol, snow/ice, speed	16	13	3	0	15	14	1	0
Distribution of snow/ice, speed	1.00	.93	.07	0				
Alcohol, wet, speed	85	65	20	0	79	70	9	0
Distribution of wet, speed	1.00	.89	.11	0				
Alcohol, dark, snow/ice, no speed	25	22	3	0	23	21	2	0
Distribution of dark, snow/ice, no speed	1.00	.92	.08	0				
Alcohol, dark, snow/ice, speed	14	12	2	0	13	11	2	0
Distribution of dark, snow/ice, speed	1.00	.81	.19	0				
Alcohol, dark, wet, speed	43	32	11	0	40	35	5	0
Distribution of dark, wet, speed	1.00	.88	.13	0				
Total	2591	1956	622	13	2417	2172	243	2

	PDO/Inj C	Injury	Fatal
Crashes by severity	1,956	622	13
Crashes by severity with countermeasure	2,172	243	2
Difference	(216)	379	11

Table 56. Impaired driver countermeasure — head-on crashes.

All alcohol crashes are to no alcohol condition
Ratio of non-alcohol crashes/all crashes = .848

					Post CM	With countermeasure		
	Total	PDO/Inj C	Injury	Fatal	Total	PDO/Inj C	Injury	Fatal
Alcohol/drugs only	567	298	237	32	481	355	116	10
Distribution of none of the above	1.00	.74	.24	.02				
Alcohol and dark only	377	178	163	36	320	224	83	13
Distribution of dark only	1.00	.70	.26	.04				
Alcohol, snow/ice, no speed	42	31	10	1	36	28	7	0
Distribution of snow/ice, no speed	1.00	.79	.20	.01				
Alcohol, snow/ice, speed	9	4	5	0	8	6	2	0
Distribution of snow/ice, speed	1.00	.74	.26	.00				
Alcohol, wet, speed	20	10	9	1	17	12	5	0
Distribution of wet, speed	1.00	.71	.27	.02				
Alcohol, dark, snow/ice, no speed	35	27	8	0	30	24	6	1
Distribution of dark, snow/ice, no speed	1.00	.79	.18	.02				
Alcohol, dark, snow/ice, speed	7	4	3	0	6	5	1	0
Distribution of dark, snow/ice, speed	1.00	.81	.17	.02				
Alcohol, dark, wet, speed	12	6	5	1	10	7	3	0
Distribution of dark, wet, speed	1.00	.68	.29	.03				
Total	1069	558	440	71	907	661	223	23

	PDO/Inj C	Injury	Fatal
Crashes by severity	558	440	71
Crashes by severity with countermeasure	661	223	23
Difference	-103	217	48

APPENDIX C.

Table 57. Vision enhancement countermeasure — run-off-the-road crashes.

All dark crashes are prorated to not dark condition
Ratio of not dark/all crashes = .613

					Post CM	With countermeasure		
	Total	PDO/Inj C	Injury	Fatal	Total	PDO/Inj C	Injury	Fatal
Dark,unlit only	5416	3956	1359	57	3320	2457	839	25
Distribution of none of the above	1.00	.74	.25	.01				
Dark and alcohol only	3830	2182	1537	111	2348	1381	924	42
Distribution of alcohol only	1.00	.59	.39	.02				
Dark, ice/snow, no speed	935	819	114	2	573	494	79	0
Distribution of snow/ice, no speed	1.00	.86	.14	.00				
Dark, snow/ice, speed	700	596	103	1	429	353	75	1
Distribution of snow/ice, speed	1.00	.82	.17	.00				
Dark, wet, speed	768	587	176	5	471	366	103	1
Distribution of wet, speed	1.00	.78	.22	.00				
Dark, alcohol, snow/ice, no speed	183	131	49	3	112	84	28	0
Distribution of alcohol, snow/ice, no speed	1.00	.75	.25	0				
Alcohol, dark, snow/ice, speed	158	118	40	0	97	64	32	1
Distribution of alcohol, snow/ice, speed	1.00	.66	.33	.01				
Alcohol, dark, wet, speed	302	172	121	9	185	122	58	5
Distribution of alcohol, wet, speed	1.00	.66	.31	.03				
Total	12292	8561	3499	188	7535	5320	2138	77

	PDO/Inj C	Injury	Fatal
Crashes by severity	8561	3499	188
Crashes by severity with countermeasure	5320	2138	77
Difference	3241	1361	111

Table 58. Vision enhancement countermeasure — vehicle strikes pedestrian/cyclist/animal.

All dark crashes are prorated to not dark condition
Ratio of not dark/all crashes = .577

					Post CM		With countermeasure	
	Total	PDO/Inj C	Injury	Fatal	Total	PDO/Inj C	Injury	Fatal
Dark only	4247	3843	354	50	2451	1401	1013	37
Distribution of none of the above	1.00	.57	.41	.02				
Alcohol and dark only	124	75	40	9	72	21	43	8
Distribution of alcohol only	1.00	.29	.60	.11				
Dark, snow/ice	324	314	7	3	187	113	70	5
Distribution of snow/ice	1.00	.60	.37	.02				
Alcohol, dark, snow/ice	8	3	5	0	5	3	2	1
Distribution of alcohol, snow/ice	1.00	.50	.33	.17				
Total	4703	4235	406	62	2714	1537	1128	50

	PDO/Inj C	Injury	Fatal
Crashes by severity	4235	406	62
Crashes by severity with countermeasure	1537	1128	50
Difference	2698	-722	12

Table 59. Vision enhancement countermeasure — crossing paths.

All dark crashes prorated to not dark condition
Ratio of non-dark/all crashes = .929

	Total	PDO/Inj C	Injury	Fatal	Post CM Total	With countermeasure PDO/Inj	With countermeasure Injury	With countermeasure Fatal
Dark, unlit only	201	164	34	3	187	156	30	0
Distribution of none of the above	1.00	.84	.16	.00				
Alcohol and dark only	25	18	6	1	23	15	7	1
Distribution of alcohol only	1.00	.66	.31	.03				
Dark, snow/ice, only	18	18	0	0	17	16	1	0
Distribution of snow/ice only	1.00	.94	.06	0				
Dark, signalized only	460	355	103	2	427	343	81	1
Distribution of signalized only	1.00	.80	.19	.00				
Dark, signed only	562	418	132	12	522	425	95	2
Distribution of signed only	1.00	.81	.18	.00				
Alcohol, dark, signalized only	106	68	37	1	98	61	36	1
Distribution of alcohol, signalized only	1.00	.62	.37	.01				
Alcohol, dark, signed only	110	65	38	7	102	67	34	2
Distribution of alcohol, signed only	1.00	.66	.33	.01				
Dark, signalized snow/ice only	35	30	5	0	33	31	2	0
Distribution of signalized, snow/ice only	1.00	.93	.07	0				
Dark, signed snow/ice only	60	53	7	0	56	52	4	0
Distribution of signed, snow/ice only	1.00	.93	.07	.00				
Alcohol, dark, snow/ice	12	6	6	0	11	8	3	0
Distribution of alcohol, snow/ice	1.00	.76	.24	0				
Total	1589	1195	368	26	1476	1174	293	7

	PDO/Inj C	Injury	Fatal
Crashes by severity	1195	368	26
Crashes by severity with countermeasure	1174	293	7
Difference	21	75	19

Table 60. Vision enhancement countermeasure — left turns.

All dark crashes are prorated to not dark condition
Ratio of non-dark/all crashes = .917

	Total	PDO/Inj C	Injury	Fatal	Post CM Total	With countermeasure PDO/Inj C	Injury	Fatal
Dark, unlit only	303	225	73	5	278	213	65	1
Distribution of none of the above	1.00	.76	.23	.00				
Alcohol and dark only	77	42	34	1	71	43	27	1
Distribution of alcohol only	1.00	.60	.38	.02				
Dark, snow/ice, only	13	12	1	0	12	11	1	0
Distribution of snow/ice only	1.00	.89	.10	0				
Dark, signalized only	387	316	69	2	355	284	70	1
Distribution of signalized only	1.00	.80	.20	.00				
Dark, signed only	61	47	14	0	56	46	10	0
Distribution of signed only	1.00	.82	.17	.00				
Alcohol, dark, signalized only	58	33	25	0	53	36	16	1
Distribution of alcohol, signalized only	1.00	.68	.31	.01				
Alcohol, dark, signed only	14	5	9	0	13	9	4	0
Distribution of alcohol, signed only	1.00	.68	.29	.02				
Dark, signalized snow/ice only	12	12	0	0	11	10	1	0
Distribution of signalized, snow/ice only	1.00	.87	.13	0				
Dark, signed snow/ice only	8	7	1	0	7	6	2	0
Distribution of signed, snow/ice only	1.00	.79	.21	0				
Alcohol, dark, snow/ice	4	3	1	0	4	3	1	0
Distribution of alcohol, snow/ice	1.00	.75	.25	0				
Total	937	702	227	8	859	659	197	4

	PDO/Inj C	Injury	Fatal
Crashes by severity	702	227	8
Crashes by severity with countermeasure	659	197	4
Difference	43	30	4

Table 61. Enhanced vision countermeasure — rear-end crashes.

All dark crashes prorated to not dark condition
Ratio of not dark/all crashes = .896

	Total	PDO/Inj C	Injury	Fatal	Post CM Total	With countermeasure PDO/Inj C	Injury	Fatal
Dark,unlit only	2684	2361	319	4	2405	2190	226	2
Distribution of none of the above	1.00	.91	.09	.00				
Dark and alcohol only	678	469	199	10	607	471	115	1
Distribution of alcohol only	1.00	.78	.19	.00				
Dark, ice/snow, no speed	265	245	20	0	237	227	10	0
Distribution of snow/ice, no speed	1.00	.96	.04	0				
Dark, snow/ice, speed	87	78	9	0	78	73	5	0
Distribution of snow/ice, speed	1.00	.93	.07	0				
Dark, wet, speed	232	203	29	0	208	185	23	0
Distribution of wet, speed	1.00	.89	.11	0				
Dark, alcohol, snow/ice, no speed	25	22	3	0	22	20	2	0
Distribution of alcohol, snow/ice, no speed	1.00	.92	.08	0				
Alcohol, dark, snow/ice, speed	14	12	2	0	13	12	1	0
Distribution of alcohol, snow/ice, speed	1.00	.90	.10	0				
Alcohol, dark, wet, speed	43	32	11	0	39	34	5	0
Distribution of alcohol, wet, speed	1.00	.88	.13	0				
Total	4028	3422	592	14	3609	3212	388	3

	PDO/Inj C	Injury	Fatal
Crashes by severity	3422	592	14
Crashes by severity with countermeasure	3212	388	3
Difference	210	204	11

Table 62. Enhanced vision countermeasure — head-on crashes.

All dark crashes are prorated to not dark condition
Ratio of not dark/all crashes = .814

					Post CM	With countermeasure		
	Total	PDO/Inj C	Injury	Fatal	Total	PDO/Inj C	Injury	Fatal
Dark,unlit only	584	408	152	24	475	350	115	10
Distribution of none of the above	1.00	.74	.24	.02				
Dark and alcohol only	377	178	163	36	307	161	128	17
Distribution of alcohol only	1.00	.53	.42	.06				
Dark, ice/snow, no speed	218	173	40	5	177	139	36	2
Distribution of snow/ice, no speed	1.00	.79	.20	.01				
Dark, snow/ice, speed	58	47	10	1	47	35	12	0
Distribution of snow/ice, speed	1.00	.74	.26	.00				
Dark, wet, speed	38	26	11	1	31	22	9	0
Distribution of wet, speed	1.00	.71	.27	.02				
Dark, alcohol, snow/ice, no speed	35	27	8	0	28	21	7	1
Distribution of alcohol, snow/ice, no speed	1.00	.74	.24	.02				
Alcohol, dark, snow/ice, speed	7	4	3	0	6	3	3	0
Distribution of alcohol, snow/ice, speed	1.00	.44	.56	0				
Alcohol, dark, wet, speed	12	6	5	1	10	5	5	1
Distribution of alcohol, wet, speed	1.00	.50	.45	.05				
Total	1329	869	392	68	1082	736	315	31

	PDO/Inj C	Injury	Fatal
Crashes by severity	869	392	76
Crashes by severity with countermeasure	736	315	31
Difference	133	77	45

APPENDIX D.

Table 63. Low-friction countermeasure — run-off-the-road crashes.

The countermeasure warns drivers of slippery conditions and to reduce speed.

- Applies only to icy/snowy or wet (low-friction) crashes.
- Does not apply to any conditions with alcohol.
- Low-friction crashes reduced by (1-number of low-friction crashes without excessive speed or alcohol)/all low-friction crashes without alcohol.
- Ratio of low-friction (no speed, no alcohol)/all low-friction (no alcohol) crashes =.40.
- Severity of remaining low-friction crashes distributed according to the distributions for low-friction, no speed conditions.

Low-friction only conditions	Total	PDO/Inj C	Injury	Fatals
Snowy/icy roads (no speed)	1974	1701	272	1
% distribution	1	.86	.14	.00
Snowy/icy roads (speed)	1298	1067	227	4
	1	.82	.17	.00
Wet and speed-related	1586	1233	348	5
	1	.78	.22	.00
Total low-friction only	4858	4001	847	10
Low-friction, dark only conditions				
Dark, snowy/icy roads (no speed)	935	819	114	2
% distribution	1	.88	.12	.00
Dark, snowy/icy roads (speed)	700	596	103	1
	1	.85	.15	.00
Dark, wet and speed-related	768	587	176	5
	1	.76	.23	.01
Total low-friction, dark only	2403	2002	393	8
Total	7261	6003	1240	18
With countermeasure				
Low-friction only	1943	1674	268	1
Low-friction, dark only	961	842	117	2
Total	2904	2516	385	3

	PDO/Inj C	Injury	Fatal
Crashes by severity	6,003	1,240	18
Crashes by severity with countermeasure	2,516	385	3
Difference	3,487	855	15

Table 64. Low-friction countermeasure — pedestrian/cyclist/animal crashes.

The countermeasure warns drivers of slippery conditions and to reduce speed.

- Applies only to icy/snowy or wet (low-friction) crashes.
- Does not apply to any conditions with alcohol.
- Low-friction crashes reduced by (1-number of low-friction crashes without excessive speed or alcohol)/all low-friction crashes without alcohol.
- Ratio of low-friction (no speed, no alcohol)/all low-friction (no alcohol) crashes =.934.
- Severity of remaining low-friction crashes distributed according to the distributions for low-friction, no speed conditions.

Low-friction only conditions	Total	PDO/Inj C	Injury	Fatals
Snowy/icy roads (no speed)	158	96	59	3
% distribution	1	.61	.37	.02
Snowy/icy roads (speed)	6	4	3	1
	1.33	.67	.50	.17
Wet and speed-related	19	7	12	0
	1	.37	.63	0
Total low-friction only	183	107	74	4
Low-friction, dark only conditions				
Dark, snowy/icy roads (no speed)	322	313	6	3
% distribution	1	.97	.02	.01
Dark, snowy/icy roads (speed)	1	1	1	0
	2	1	1	0
Dark, wet and speed-related	8	8	1	0
	1.13	1	.13	0
Total low-friction, dark only	331	322	8	3
Total	514	429	82	7
With countermeasure				
Low-friction only	171	104	64	3
Low-friction, dark only	309	300	6	3
Total	480	404	70	6

	PDO/Inj C	Injury	Fatal
Crashes by severity	429	82	7
Crashes by severity with countermeasure	404	70	6
Difference	25	12	1

Table 65. Low-friction countermeasure — crossing-path crashes.

The countermeasure warns drivers of slippery conditions and to reduce speed.

- Applies only to icy/snowy or wet (low-friction) crashes.
- Does not apply to any conditions with alcohol.
- Low-friction crashes reduced by (1-number of low-friction crashes without excessive speed or alcohol)/all low-friction crashes without alcohol.
- Ratio of low-friction (no speed, no alcohol)/all low-friction (no alcohol) crashes =.79.
- Severity of remaining low-friction crashes distributed according to the distributions for low-friction, no speed conditions.

Low-friction only conditions	Total	PDO/Inj C	Injury	Fatals
Snowy/icy roads (no speed)	1017	948	68	1
% distribution	1	.93	.07	.00
Snowy/icy roads (speed)	113	107	6	0
	1	.95	.05	0
Wet and speed-related	153	114	38	1
	1	.75	.25	.01
Total low-friction only	1283	1169	112	2
Low-friction, dark only conditions				
Dark, snowy/icy roads (no speed)	96	87	9	0
% distribution	1	.91	.09	0
Dark, snowy/icy roads (speed)	17	14	3	0
	1	.82	.18	0
Dark, wet and speed-related	12	8	4	0
	1	.67	.33	0
Total low-friction, dark only	125	109	16	0
Total	1408	1278	128	2
With countermeasure				
Low-friction only	1014	945	68	1
Low-friction, dark only	99	89	9	0
Total	1112	1034	77	1

	PDO/Inj C	Injury	Fatal
Crashes by severity	1,278	128	2
Crashes by severity with countermeasure	1,034	77	1
Difference	44	51	1

Table 66. Low-friction countermeasure — left turns.

The countermeasure warns drivers of slippery conditions and to reduce speed.

- Applies only to icy/snowy or wet (low-friction) crashes.
- Does not apply to any conditions with alcohol.
- Low-friction crashes reduced by (1-number of low-friction crashes without excessive speed or alcohol)/all low-friction crashes without alcohol.
- Ratio of low-friction (no speed, no alcohol)/all low-friction (no alcohol) crashes =.757.
- Severity of remaining low-friction crashes distributed according to the distributions for low-friction, no speed conditions.

Low-friction only conditions	Total	PDO/Inj C	Injury	Fatals
Snowy/icy roads (no speed)	217	187	30	0
% distribution	1	.86	.14	0
Snowy/icy roads (speed)	14	14	0	0
	1	1	0	0
Wet and speed-related	59	46	13	0
	1	.78	.22	0
Total low-friction only	290	247	43	0
Low-friction, dark only conditions				
Dark, snowy/icy roads (no speed)	30	28	2	0
% distribution	1	.93	.07	0
Dark, snowy/icy roads (speed)	3	3	0	0
	1	1	0	0
Dark, wet and speed-related	3	3	0	0
	1	1	0	0
Total low-friction, dark only	36	34	2	0
Total	326	281	45	0
With countermeasure				
Low-friction only	220	189	30	0
Low-friction, dark only	27	25	2	0
Total	247	215	32	0

	PDO/Inj C	Injury	Fatal
Crashes by severity	281	45	0
Crashes by severity with countermeasure	215	32	0
Difference	66	13	0

Table 67. Low-friction countermeasure — rear-end crashes.

The countermeasure warns drivers of slippery conditions and to reduce speed.

- Applies only to icy/snowy or wet (low-friction) crashes.
- Does not apply to any conditions with alcohol.
- Low-friction crashes reduced by (1-number of low-friction crashes without excessive speed or alcohol)/all low-friction crashes without alcohol.
- Ratio of low-friction (no speed, no alcohol)/all low-friction (no alcohol) crashes =.41.
- Severity of remaining low-friction crashes distributed according to the distributions for low-friction, no speed conditions.

Low-friction only conditions	Total	PDO/Inj C	Injury	Fatals
Snowy/icy roads (no speed)	1658	1590	68	0
% distribution	1	.96	.04	0
Snowy/icy roads (speed)	410	383	27	0
	1	.93	.07	0
Wet and speed-related	2032	1805	227	0
	1	.89	.11	0
Total low-friction only	4100	3778	322	0
Low-friction, dark only conditions				
Dark, snowy/icy roads (no speed)	265	245	20	0
% distribution	1	.92	.08	0
Dark, snowy/icy roads (speed)	87	78	9	0
	1	.90	.10	0
Dark, wet and speed-related	232	203	29	0
	1	.88	.13	0
Total low-friction, dark only	584	526	58	0
Total	4684	4304	380	0
With countermeasure				
Low-friction only	1681	1612	69	0
Low-friction, dark only	239	221	18	0
Total	1920	1833	87	0

	PDO/Inj C	Injury	Fatal
Crashes by severity	4,304	380	0
Crashes by severity with countermeasure	1,833	87	0
Difference	2,471	293	0

Table 68. Low-friction countermeasure — head-on crashes.

The countermeasure warns drivers of slippery conditions and to reduce speed.

- Applies only to icy/snowy or wet (low-friction) crashes.
- Does not apply to any conditions with alcohol.
- Low-friction crashes reduced by (1-number of low-friction crashes without excessive speed or alcohol)/all low-friction crashes without alcohol.
- Ratio of low-friction (no speed, no alcohol)/all low-friction (no alcohol) crashes =.36.
- Severity of remaining low-friction crashes distributed according to the distributions for low-friction, no speed conditions.

Low-friction only conditions	Total	PDO/Inj C	Injury	Fatals
Snowy/icy roads (no speed)	920	724	185	11
% distribution	1	.79	.20	.01
Snowy/icy roads (speed)	209	154	54	1
	1	.74	.26	.00
Wet and speed-related	324	230	89	5
	1	.71	.27	.02
Total low-friction only	1453	1108	328	17
Low-friction, dark only conditions				
Dark, snowy/icy roads (no speed)	218	173	40	5
% distribution	1	.79	.18	.02
Dark, snowy/icy roads (speed)	58	47	10	1
	1	.81	.17	.02
Dark, wet and speed-related	38	26	11	1
	1	.68	.29	.03
Total low-friction, dark only	314	246	61	7
Total	1767	1354	389	24
With countermeasure				
Low-friction only	523	412	105	6
Low-friction, dark only	113	90	21	3
Total	636	501	126	9

	PDO/Inj C	Injury	Fatal
Crashes by severity	1,354	389	24
Crashes by severity with countermeasure	501	126	9
Difference	853	263	15

APPENDIX E.

Table 69. Headway countermeasure — rear-end crashes — nominal + dark only PDO and/or injury C severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM **
0 - 10	4.50%	1281.11	0	3	0
11 - 20	7.60%	2163.64	0	9	0
21 - 30	18.20%	5181.36	0	15	0
31 - 40	38.80%	11045.97	0	21	0
41 - 50	20.90%	5950.02	4.70	27	298
51 - 60	4.30%	1224.17	15.00	33	393
61 - 70	3.70%	1053.35	22.36	39	743
> 71	2.00%	569.38	29.10	45	512
Total		28469.00			1946

* Distribution of travel speed of striking vehicles in rear-end crashes with severity PDO and/or injury C in NASS file.

** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ***	No. of PDO Crashes Remaining
41 - 50	5950.02	.05000	297.50
51 - 60	1224.17	.32131	393.34
61 - 70	1053.35	.70510	742.72
> 71	569.38	.90000	512.44

*** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration).

Table 70. Headway countermeasure — rear-end crashes — nominal + dark only injury A and B severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM **	No. of PDO After CM
0 - 10	.50%	15.17	0	3	0	0
11 - 20	5.60%	169.85	0	9	0	0
21 - 30	13.80%	418.55	0	15	0	0
31 - 40	19.00%	576.27	0	21	0	0
41 - 50	31.40%	952.36	4.70	27	7	945
51 - 60	11.80%	357.89	15.00	33	87	271
61 - 70	13.70%	415.52	22.36	39	169	247
> 71	4.30%	130.42	29.10	45	92	39
Total	100.00%	3033			354	1502

* Distribution of travel speed of striking vehicles in rear-end crashes with injury A and B severity in NASS file.

** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ***	No. of Inj Crashes Remaining
41 - 50	952.36	.00711	6.77
51 - 60	357.89	.24239	86.75
61 - 70	415.52	.40605	168.72
> 71	130.42	.70230	91.59

*** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

Table 71. Headway countermeasure — rear-end crashes — nominal + dark only fatal accidents.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM **	No. of PDO After CM
0 - 10	.00%	0	0	3	0	0
11 - 20	.00%	0	0	9	0	0
21 - 30	.00%	0	0	15	0	0
31 - 40	11.70%	2.69	0	21	0	3
41 - 50	28.50%	6.56	4.70	27	0	7
51 - 60	30.20%	6.95	15.00	33	0	7
61 - 70	17.70%	4.07	22.36	39	1	3
> 71	11.90%	2.74	29.10	45	1	1
Total	100.00%	23			2	21

* Distribution of travel speed of striking vehicles in rear-end crashes with fatal severity in NASS file.

** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ***	No. of Fatal Crashes Remaining
41 - 50	6.56	0	0
51 - 60	6.95	0	0
61 - 70	4.07	.13280	.54
> 71	2.74	.40200	1.10

*** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration).

Table 72. Headway countermeasure — rear-end crashes — low-friction PDO and/or injury C severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM *
0 - 10	4.50%	193.68	0	3	0
11 - 20	7.60%	327.10	3.21	9	122
21 - 30	18.20%	783.33	10.35	15	313
31 - 40	38.80%	1669.95	16.62	21	732
41 - 50	20.90%	899.54	22.74	27	691
51 - 60	4.30%	185.07	28.81	33	176
61 - 70	3.70%	159.25	34.85	39	152
> 71	2.00%	86.08	40.88	45	84
Total		4304.00			2270

* Distribution of travel speed of striking vehicles in rear-end crashes with severity PDO and/or injury C in NASS file.

** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of crashes Remaining ***	No. of PDO Crashes Remaining
11 - 20	327.10	.37190	121.65
21 - 30	783.33	.39934	312.81
31 - 40	1669.95	.43849	732.27
41 - 50	899.54	.76778	690.64
51 - 60	185.07	.95212	176.21
61 - 70	159.25	.95693	152.39
> 71	86.08	.97131	83.61

*** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration).

Table 73. Headway countermeasure — rear-end crashes — low-friction injury A and B severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM **	No. of PDO After CM
0 - 10	.50%	1.90	0	3	0	0
11 - 20	5.60%	21.28	3.21	9	2	20
21 - 30	13.80%	52.44	10.35	15	16	36
31 - 40	19.00%	72.20	16.62	21	37	35
41 - 50	31.40%	119.32	22.74	27	66	53
51 - 60	11.80%	44.84	28.81	33	38	7
61 - 70	13.70%	52.06	34.85	39	44	8
> 71	4.30%	16.34	40.88	45	15	1
Total	100.00%	380			219	160

* Distribution of travel speed of striking vehicles in rear-end crashes with injury A and B severity in NASS file.

** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ***	No. of Injury Crashes Remaining
11 - 20	21.28	.08197	1.74
21 - 30	52.44	.30653	16.07
31 - 40	72.20	.51157	36.94
41 - 50	119.32	.55334	66.02
51 - 60	44.84	.85539	38.36
61 - 70	52.06	.84727	44.11
> 71	16.34	.94638	15.46

*** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

Table 74. Headway countermeasure — rear-end crashes — low-friction fatal accidents.

Travel Speed	PDO/Inj C Dist From NASS *	No. of crashes in CARDile Sample	Delta V After CM	Reference Delta V	No. of Fatal Crashes After CM **	No. of Injury Crashes After CM
0 - 10	.00%	0	0	3	0	0
11 - 20	.00%	0	3.21	9	0	0
21 - 30	.00%	0	10.35	15	0	0
31 - 40	11.70%	0	16.62	21	0	0
41 - 50	28.50%	0	22.74	27	0	0
51 - 60	30.20%	0	28.81	33	0	0
61 - 70	17.70%	0	34.85	39	0	0
> 71	11.90%	0	40.88	45	0	0
Total	100.00%	0			0	0

* Distribution of travel speed of striking vehicles in rear-end crashes with fatal severity in NASS file.

** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ***	No. of Fatal Crashes Remaining
11 - 20	0	0	0
21 - 30	0	0	0
31 - 40	0	0	0
41 - 50	0	0	0
51 - 60	0	0	0
61 - 70	0	0	0
> 71	0	0	0

*** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

APPENDIX F.

Table 75. Braking countermeasure — pedestrian/cyclist/animal crashes — nominal + dark only PDO and/or injury C severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample	Delta V After CM	Reference Delta V	No. of Crashes After CM **
0 - 10	4.50%	329.58	0	3	0
11 - 20	7.60%	556.62	0	9	0
21 - 30	18.20%	1332.97	0	15	0
31 - 40	38.80%	2841.71	0	21	0
41 - 50	20.90%	1530.72	16.71	27	515
51 - 60	4.30%	314.93	26.79	33	301
61 - 70	3.70%	270.99	35.05	39	261
≥ 71	2.00%	146.48	42.55	45	144
Total		7324.00			1221

* Since the distribution of travel speeds for pedestrian accidents is not available from the NASS file, the distribution of travel speed of striking vehicles in rear-end crashes with severity PDO and/or injury C was used.

** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ***	No. of PDO Crashes Remaining
41 - 50	1530.72	.33667	515.34
51 - 60	314.93	.95440	300.57
61 - 70	270.99	.96224	260.76
≥ 71	146.48	.98000	143.55

*** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration).

Table 76. Braking countermeasure — pedestrian/cyclist/animal crashes — nominal + dark only injury A and B severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM **	No. of PDO After CM
0 - 10	.50%	14.36	0	3	0	0
11 - 20	5.60%	160.83	0	9	0	0
21 - 30	13.80%	396.34	0	15	0	0
31 - 40	19.00%	545.68	0	21	0	0
41 - 50	31.40%	901.81	16.71	27	255	647
51 - 60	11.80%	338.90	26.79	33	290	49
61 - 70	13.70%	393.46	35.05	39	337	56
> 71	4.30%	123.50	42.55	45	118	5
Total	100.00%	2872			1000	757

* Since the distribution of travel speeds for pedestrian accidents is not available from the NASS file, the distribution of travel speed of striking vehicles in rear-end crashes with severity of injury A and B was used.

** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ***	No. of Injury Crashes Remaining
41 - 50	901.81	.28307	255.28
51 - 60	338.90	.85627	290.19
61 - 70	393.46	.85699	337.20
> 71	123.50	.95704	118.19

*** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

Table 77. Braking countermeasure — pedestrian/cyclist/animal crashes — nominal + dark only fatal severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM **	No. of PDO After CM
0 - 10	.00%	0	0	3	0	0
11 - 20	.00%	0	0	9	0	0
21 - 30	.00%	0	0	15	0	0
31 - 40	11.70%	16.61	0	21	0	0
41 - 50	28.50%	40.47	16.71	27	0	40
51 - 60	30.20%	42.88	26.79	33	24	19
61 - 70	17.70%	25.13	35.05	39	20	5
≥ 71	11.90%	16.90	42.55	45	15	2
Total	100.00%	142			59	66

* Since the distribution of travel speeds for pedestrian accidents is not available from the NASS file, the distribution of travel speed of striking vehicles in rear-end crashes with fatal severity was used.

** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ***	No. of Fatal Crashes Remaining
41 - 50	40.47	0	0
51 - 60	42.88	.57102	24.49
61 - 70	25.13	.79909	20.08
≥ 71	16.90	.88100	14.89

*** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

Table 78. Braking countermeasure — pedestrian/cyclist/animal crashes — low-friction conditions PDO and/or injury C severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample	Delta V After CM	Reference Delta V	No. of Crashes After CM **
0 - 10	4.50%	18.63	0	3	0
11 - 20	7.60%	31.46	2.27	9	12
21 - 30	18.20%	75.35	7.33	15	30
31 - 40	38.80%	160.63	16.81	21	70
41 - 50	20.90%	86.53	24.37	27	83
51 - 60	4.30%	17.80	31.27	33	18
61 - 70	3.70%	15.32	37.86	39	15
≥ 71	2.00%	8.28	44.28	45	8
Total		414.00			236

* Since the distribution of travel speeds for pedestrian accidents is not available from the NASS file, the distribution of travel speed of striking vehicles in rear-end crashes with severity PDO and/or injury C was used.

** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ***	No. of PDO Crashes Remaining
11 - 20	31.46	.37190	11.70
21 - 30	75.35	.39934	30.09
31 - 40	160.63	.43849	70.44
41 - 50	86.53	.95440	82.58
51 - 60	17.80	1	17.80
61 - 70	15.32	1	15.32
≥ 71	8.28	1	8.28

*** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration).

Table 79. Braking countermeasure — pedestrian/cyclist/animal crashes — low-friction conditions injury A and B severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM **	No. of PDO After CM
0 - 10	.50%	.35	0	3	0	0
11 - 20	5.60%	3.86	2.27	9	0	4
21 - 30	13.80%	9.52	7.33	15	3	7
31 - 40	19.00%	13.11	16.81	21	7	6
41 - 50	31.40%	21.67	24.37	27	19	3
51 - 60	11.80%	8.14	31.27	33	8	0
61 - 70	13.70%	9.45	37.86	39	9	0
≥ 71	4.30%	2.97	44.28	45	3	0
Total	100.00%	69			49	20

* Since the distribution of travel speeds for pedestrian accidents is not available from the NASS file, the distribution of travel speed of striking vehicles in rear-end crashes with severity of injury A and B was used.

** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ***	No. of Injury Crashes Remaining
11 - 20	3.86	.08197	.32
21 - 30	9.52	.30653	2.92
31 - 40	13.11	.51157	6.71
41 - 50	21.67	.85627	18.55
51 - 60	8.14	1	8.14
61 - 70	9.45	1	9.45
≥ 71	2.97	1	2.97

*** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

Table 80. Braking countermeasure — pedestrian/cyclist/animal crashes — low-friction conditions fatal severity

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM **	No. of PDO After CM
0 - 10	.00%	0	0	3	0	0
11 - 20	.00%	0	2.27	9	0	0
21 - 30	.00%	0	7.33	15	0	0
31 - 40	11.70%	.82	16.81	21	0	1
41 - 50	28.50%	2.00	24.37	27	2	0
51 - 60	30.20%	2.11	31.27	33	2	0
61 - 70	17.70%	1.24	37.86	39	1	0
≥ 71	11.90%	.83	44.28	45	1	0
Total	100.00%	7			6	1

* Since the distribution of travel speeds for pedestrian accidents is not available from the NASS file, the distribution of travel speed of striking vehicles in rear-end crashes with fatal severity was used.

** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ***	No. of Fatal Crashes Remaining
11 - 20	0	.37190	0
21 - 30	0	.39934	0
31 - 40	.82	.43849	.36
41 - 50	2.00	.95440	1.90
51 - 60	2.11	1	2.11
61 - 70	1.24	1	1.24
≥ 71	.83	1	.83

*** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

APPENDIX G.

Table 81. Run-off-the-road lateral lane-edge detection and steering correction countermeasure on tangent sections of road PDO and/or injury C severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample**	Delta V After CM	Reference Delta V	No. of Crashes After CM ***
0 - 10	1.90%	126.33	0	3	0
11 - 20	6.30%	418.89	0	9	0
21 - 30	12.40%	824.48	0	15	0
31 - 40	23.40%	1556.10	0	21	0
41 - 50	27.50%	1828.75	0	27	0
51 - 60	21.50%	1429.75	0	33	0
61 - 70	6.50%	432.25	20.92	39	191
≥ 71	.60%	39.90	31.32	45	37
Total	100.00%	6656			228

* Distribution of travel speed of striking vehicles in run-off-the-road crashes with PDO or injury C severity in NASS file.

** It is assumed that this countermeasure would not be effective in cases involving alcohol. It is assumed that in 50 percent of the cases, the driver will steer to safety. The numbers in this column represent those cases where brakes are applied.

*** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ****	No. of PDO Crashes Remaining
61 - 70	432.25	.44219	191.14
≥ 71	39.90	.92907	37.07

****The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration).

Table 82. Run-off-the-road lateral lane-edge detection and steering correction countermeasure on horizontal curves PDO and/or injury C severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample**	Delta V After CM	Reference Delta V	No. of Crashes After CM ***
0 - 10	1.90%	73.19	0	3	0
11 - 20	6.30%	242.68	0	9	0
21 - 30	12.40%	477.65	0	15	0
31 - 40	23.40%	901.37	11.50	21	168
41 - 50	27.50%	1059.03	21.44	27	652
51 - 60	21.50%	827.97	29.30	33	637
61 - 70	6.50%	250.38	36.47	39	234
≥ 71	.60%	23.11	43.28	45	23
Total	100.00%	3855			1714

* Distribution of travel speed of striking vehicles in run-off-the-road crashes with PDO or injury C severity in NASS file.

** It is assumed that this countermeasure would not be effective in cases involving alcohol. It is assumed that in 17 percent of the cases, the driver will steer to safety. The numbers in this column represent those cases where brakes are applied.

*** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ****	No. of PDO Crashes Remaining
31 - 40	901.37	.1864	167.98
41 - 50	1059.03	.6154	651.77
51 - 60	827.97	.7688	636.58
61 - 70	250.38	.9347	234.02
≥ 71	23.11	1	23.11

**** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration).

Table 83. Run-off-the-road lateral lane-edge detection and steering correction countermeasure on tangent sections of road injury A and B severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile sample**	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM ***	No. of PDO After CM
0 - 10	1.50%	28.65	0	3	0	0
11 - 20	1.60%	30.56	0	9	0	0
21 - 30	7.70%	147.07	0	15	0	0
31 - 40	19.90%	380.09	0	21	0	0
41 - 50	22.60%	431.66	0	27	0	0
51 - 60	29.80%	569.18	0	33	0	0
61 - 70	13.00%	248.30	20.92	39	79	169
> 71	3.90%	74.49	31.32	45	62	13
Total	100.00%	1912	141	182		

* Distribution of travel speed of striking vehicles in run-off-the-road crashes with injury A and B severity in NASS file.

** It is assumed that this countermeasure would not be effective in cases involving alcohol. It is assumed that in 50 percent of the cases, the driver will steer to safety. The numbers in this column represent those cases where brakes are applied.

*** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. oOf Crashes	Portion of Crashes Remaining ****	No. of Injury Crashes Remaining
61 - 70	248.30	.31946	79.32
> 71	74.49	.83100	61.90

**** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

Table 84. Run-off-the-road lateral lane-edge detection and steering correction countermeasure on horizontal curves injury A and B severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample**	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM ***	No. of PDO After CM
0 - 10	1.90%	24.51	0	3	0	0
11 - 20	6.30%	81.27	0	9	0	0
21 - 30	12.40%	159.96	0	15	0	0
31 - 40	23.40%	301.86	11.50	21	56	246
41 - 50	27.50%	354.75	21.44	27	218	137
51 - 60	21.50%	277.35	29.30	33	213	64
61 - 70	6.50%	83.85	36.47	39	78	6
> 71	.60%	7.74	43.28	45	8	0
Total	100.00%	1291			574	453

* Distribution of travel speed of striking vehicles in run-off-the road-crashes with PDO or injury C severity in NASS file.

** It is assumed that this countermeasure would not be effective in cases involving alcohol. It is assumed that in 17 percent of the cases, the driver will steer to safety. The numbers in this column represent those cases where brakes are applied.

*** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ****	No. of Injury Crashes Remaining
31 - 40	301.86	.1864	56.26
41 - 50	354.75	.6154	218.31
51 - 60	277.35	.7688	213.23
61 - 70	83.85	.9347	78.37
> 71	7.74	1	7.74

**** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

Table 85. Run-off-the-road lateral lane-edge detection and steering correction countermeasure on tangent sections of road fatal accidents.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample**	Delta V After CM	Reference Delta V	No. of Fatal Crashes After CM ***	No. of Injury Crashes after CM
0 - 10	.80%	.44	0	3	0	0
11 - 20	.00%	0	0	9	0	0
21 - 30	2.80%	1.54	0	15	0	0
31 - 40	5.30%	2.92	0	21	0	0
41 - 50	10.90%	6.00	0	27	0	0
51 - 60	22.50%	12.38	0	33	0	0
61 - 70	31.30%	17.22	20.92	39	2	15
> 71	26.30%	14.47	31.32	45	6	8
Total	100.00%	55			8	23

* Distribution of travel speed of striking vehicles in run-off-the-road crashes with fatal severity in NASS file.

** It is assumed that this countermeasure would not be effective in cases involving alcohol. It is assumed that in 50 percent of the cases the driver will steer to safety. The numbers in this column represent those cases where brakes are applied.

*** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ****	No. of Fatal Crashes Remaining
61 - 70	17.22	12092	2.08
≥ 71	14.47	.42342	6.12

**** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

Table 86. Run-off-the-road lateral lane-edge detection and steering correction countermeasure on horizontal curves fatal accidents.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample*	Delta V After CM	Reference Delta V	No. of Fatal Crashes After CM **	No. of Injury Crashes After CM
0 - 10	.80%	.32	0	3	0	0
11 - 20	.00%	0	0	9	0	0
21 - 30	2.80%	1.12	0	15	0	0
31 - 40	5.30%	2.12	11.50	21	0	2
41 - 50	10.90%	4.36	21.44	27	2	2
51 - 60	22.50%	9.00	29.30	33	4	5
61 - 70	31.30%	12.52	36.47	39	7	5
> 71	26.30%	10.52	43.28	45	11	0
Total	100.00%	40			24	14

* Distribution of travel speed of striking vehicles in rear-end crashes with fatal severity in NASS file.

** It is assumed that this countermeasure would not be effective in cases involving alcohol. It is assumed that in 17 percent of the cases, the driver will steer to safety. The numbers in this column represent those cases where brakes are applied.

*** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ****	No. of Fatal Crashes Remaining
31 - 40	2.12	.0899	.19
41 - 50	4.36	.4495	1.96
51 - 60	9.00	.4681	4.21
61 - 70	12.52	.5747	7.20
> 71	10.52	1	10.52

**** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

APPENDIX H.

Table 87. Run-off-the-road lateral lane-edge detection warning and steering correction with preview countermeasure on tangent sections of road PDO and/or injury C severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample**	Delta V After CM	Reference Delta V	No. of Crashes After CM ***
0 - 10	1.90%	63.19	0	3	0
11 - 20	6.30%	209.54	0	9	0
21 - 30	12.40%	412.30	0	15	0
31 - 40	23.40%	778.05	0	21	0
41 - 50	27.50%	914.38	0	27	0
51 - 60	21.50%	714.88	0	33	0
61 - 70	6.50%	216.19	13.50	39	89
> 71	.60%	19.96	26.20	45	29
Total	100.00%	3328			118

* Distribution of travel speed of striking vehicles in run-off-the-road crashes with PDO or injury C severity in NASS file.

** It is assumed that this countermeasure would not be effective in cases involving alcohol. It is assumed that in 75 percent of the cases, the driver will steer to safety. The numbers in this column represent those cases where brakes are applied.

*** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ****	No. of PDO Crashes Remaining
61 - 70	432.25	.20705	89.50
> 71	39.90	.71428	28.50

**** The portion of crashes remaining at the same severity for each cell is equal to the cumulative number of crashes up to point where reference delta V matches the after CM delta C)/(cumulative number of crashes up to the cell under consideration).

Table 88. Run-off-the-road lateral lane-edge detection warning and steering correction with preview countermeasure on horizontal curves PDO and/or injury C severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample**	Delta V After CM	Reference Delta V	No. of crashes After CM ***
0 - 10	1.90%	22.06	0	3	0
11 - 20	6.30%	73.14	0	9	0
21 - 30	12.40%	143.96	0	15	0
31 - 40	23.40%	271.44	12.49	21	127
41 - 50	27.50%	319.00	22.86	27	196
51 - 60	21.50%	249.40	31.00	33	249
61 - 70	6.50%	75.47	38.36	39	75
≥ 71	.60%	6.97	45.00	45	7
Total	100.00%	1161			1654

* Distribution of travel speed of striking vehicles in run-off-the-road crashes with PDO or injury C severity in NASS file.

** It is assumed that this countermeasure would not be effective in cases involving alcohol. It is assumed that in 75 percent of the cases, the driver will steer to safety. The numbers in this column represent those cases where brakes are applied.

*** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ****	No. of PDO Crashes Remaining
31 - 40	271.44	.4682	127.14
41 - 50	319.00	.6154	196.34
51 - 60	249.40	1	249.40
61 - 70	75.47	1	75.47
≥ 71	6.97	1	6.97

**** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration).

Table 89. Run-off-the-road lateral lane-edge detection warning and steering correction with preview countermeasure on tangent sections of road injury A and B severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample**	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM ***	No. of PDO After CM
0 - 10	1.50%	14.34	0	3	0	0
11 - 20	1.60%	15.30	0	9	0	0
21 - 30	7.70%	73.61	0	15	0	0
31 - 40	19.90%	190.05	0	21	0	0
41 - 50	22.60%	215.83	0	27	0	0
51 - 60	29.80%	284.89	0	33	0	0
61 - 70	13.00%	124.28	13.50	39	26	98
> 71	3.90%	37.28	26.20	45	27	10
Total	100.00%	956			53	108

* Distribution of travel speed of striking vehicles in run-off-the-road crashes with injury A and B severity in NASS file.

** It is assumed that this countermeasure would not be effective in cases involving alcohol. It is assumed that in 75 percent of the cases, the driver will steer to safety. The numbers in this column represent those cases where brakes are applied.

*** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ****	No. of Injury Crashes Remaining
61 - 70	124.28	.20705	25.73
≥ 71	37.28	.71428	26.63

****The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

Table 90. Run-off-the-road lateral lane-edge detection warning and steering correction with preview countermeasure on horizontal curves injury A and B severity.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile Sample**	Delta V After CM	Reference Delta V	No. of Inj Crashes After CM ***	No. of PDO After CM
0 - 10	1.50%	5.84	0	3	0	0
11 - 20	1.60%	6.22	0	9	0	0
21 - 30	7.70%	29.95	0	15	0	0
31 - 40	19.90%	77.41	12.49	21	36	41
41 - 50	22.60%	87.91	22.86	27	54	34
51 - 60	29.80%	115.92	31.00	33	116	0
61 - 70	13.00%	50.57	38.36	39	51	0
> 71	3.90%	15.17	45.00	45	15	0
Total	100.00%	389			272	75

* Distribution of travel speed of striking vehicles in run-off-the-road crashes with PDO or injury C severity in NASS file.

** It is assumed that this countermeasure would not be effective in cases involving alcohol. It is assumed that in 75 percent of the cases, the driver will steer to safety. The numbers in this column represent those cases where brakes are applied.

*** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ****	No. of Injury Crashes Remaining
31 - 40	77.41	.4682	36.24
41 - 50	87.91	.6154	54.10
51 - 60	115.92	1	115.92
61 - 70	50.57	1	50.57
> 71	15.17	1	15.17

**** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

Table 91. Run-off-the-road lateral lane-edge detection warning and steering correction with preview countermeasure on tangent sections of road fatal accidents.

Travel Speed	PDO/Inj C Dist From NASS *	No. of Crashes in CARDfile sample**	Delta V After CM	Reference Delta V	No. of fatal crashes After CMm ***	No. of Injury Crashes after CM
0 - 10	.80%	.21	0	3	0	0
11 - 20	.00%	0	0	9	0	0
21 - 30	2.80%	.73	0	15	0	0
31 - 40	5.30%	1.38	0	21	0	0
41 - 50	10.90%	2.83	0	27	0	0
51 - 60	22.50%	5.85	0	33	0	0
61 - 70	31.30%	8.14	13.50	39	2	6
> 71	26.30%	6.84	26.20	45	5	2
Total	100.00%	26			7	8

* Distribution of travel speed of striking vehicles in run-off-the-road crashes with fatal severity in NASS file.

** It is assumed that this countermeasure would not be effective in cases involving alcohol. It is assumed that in 75 percent of the cases, the driver will steer to safety. The numbers in this column represent those cases where brakes are applied.

*** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of Crashes Remaining ****	No. of Fatal Crashes Remaining
61 - 70	8.14	.20705	1.68
≥ 71	6.84	.71428	4.88

**** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

Table 92. Run-off-the-road lateral lane-edge detection warning and steering correction with preview countermeasure on horizontal curves fatal accidents.

Travel Speed	PDO/Inj C Dist From nass *	No. of Crashes in CARDfile Sample**	Delta V After CM	Reference Delta V	No. of Fatal Crashes After CM ***	No. of Injury Crashes after CM
0 - 10	.80%	.10	0	3	0	0
11 - 20	.00%	0	0	9	0	0
21 - 30	2.80%	.34	0	15	0	0
31 - 40	5.30%	.64	12.49	21	0	0
41 - 50	10.90%	1.31	22.86	27	1	1
51 - 60	22.50%	2.70	31.00	33	3	0
61 - 70	31.30%	3.76	38.36	39	4	0
> 71	26.30%	3.16	45.00	45	3	0
Total	100.00%	12			11	1

* Distribution of travel speed of striking vehicles in rear-end crashes with fatal severity in NASS file.

** It is assumed that this countermeasure would not be effective in cases involving alcohol. It is assumed that in 75 percent of the cases, the driver will steer to safety. The numbers in this column represent those cases where brakes are applied.

*** Reduction of severity calculations for those cases where delta V with CM is not 0.

Travel Speed	No. of Crashes	Portion of crashes Remaining ****	No. of Fatal Crashes Remaining
31 - 40	.64	.4682	.30
41 - 50	1.31	.6154	.80
51 - 60	2.70	1	2.70
61 - 70	3.76	1	3.76
> 71	3.16	1	3.16

**** The portion of crashes remaining at the same severity for each cell is equal to the (cumulative number of crashes up to point where reference delta V matches the after CM delta V)/(cumulative number of crashes up to the cell under consideration). The severity of the other crashes in the cell is reduced by one category of severity.

APPENDIX I.

Table 93. Run-off-the-road dynamic horizontal curve speed advisory countermeasure PDO and injury C severity.

Wet Conditions

Travel Speed	PDO/Inj C Dist From NASS *	No. of Affected Crashes in CARDfile Sample	CM Advisory Speed	No. of Crashes After CM **	Rounded Off
0 - 10	1.90%	12.56	23.49	12.56	13
11 - 20	6.30%	41.64	23.49	41.64	42
21 - 30	12.40%	81.96	23.49	81.96	82
31 - 40	23.40%	154.67	32.45	154.67	155
41 - 50	27.50%	181.78	43.93	181.78	182
51 - 60	21.50%	142.12	53.79	142.12	142
61 - 70	6.50%	42.97	68.06	0	0
> 71	.60%	3.97	68.06	0	0
Total	100%	662		614.73	615

Icy/Snowy Conditions

Travel Speed	PDO/Inj C Dist From NASS *	No. of Affected Crashes in CARDfile Sample	CM Advisory Speed	No. of Crashes After CM **	Rounded Off
0 - 10	1.90%	18.47	15.66	18.4718	19
11 - 20	6.30%	61.24	15.66	61.24	61
21 - 30	12.40%	120.53	15.66	0	0
31 - 40	23.40%	227.21	21.63	0	0
41 - 50	27.50%	267.03	29.29	0	0
51 - 60	21.50%	208.98	35.86	0	0
61 - 70	6.50%	63.18	45.37	0	0
> 71	.60%	5.83	45.37	0	0
Total	100%	972		79.70	80

* Speed distribution from run-off-the-road accidents in NASS file.

** It is assumed that if the vehicle is traveling at a speed greater than the CM advisory speed, the driver will slow down and the accident does not occur.

Table 94. Run-off-the-road dynamic horizontal curve speed advisory countermeasure injury A and B severity.

Wet Conditions

Travel Speed	PDO/Inj C Dist From NASS *	No. of Affected Crashes in CARDfile sample	CM Advisory Speed	No. of Crashes After CM **	Rounded Off
0 - 10	1.50%	3.06	23.49	3.06	3
11 - 20	1.60%	3.26	23.49	3.26	3
21 - 30	7.70%	15.71	23.49	15.71	16
31 - 40	19.90%	40.60	32.45	40.60	41
41 - 50	22.60%	46.10	43.93	46.10	46
51 - 60	29.80%	60.79	53.79	60.79	61
61 - 70	13.00%	26.52	68.06	26.52	27
> 71	3.90%	7.96	68.06	0	0
Total	100%	204		196.04	196

Icy/Snowy Conditions

Travel Speed	PDO/Inj C Dist From NASS *	No. of affected Crashes in CARDfile Sample	CM Advisory Speed	No. of Crashes After CM **	Rounded Off
0 - 10	1.50%	2.99	15.66	2.99	3
11 - 20	1.60%	3.18	15.66	3.18	3
21 - 30	7.70%	15.32	15.66	0	0
31 - 40	19.90%	39.60	21.63	0	0
41 - 50	22.60%	44.97	29.29	0	0
51 - 60	29.80%	59.30	35.86	0	0
61 - 70	13.00%	25.87	45.37	0	0
> 71	3.90%	7.76	45.37	0	0
Total	100%	199		6.17	6

* Speed distribution from run-off-the-road accidents in NASS file.

** It is assumed that if the vehicle is traveling at a speed greater than the CM advisory speed, the driver will slow down and the accident does not occur.

Table 95. Run-off-the-road dynamic horizontal curve speed advisory countermeasure fatal accidents.

Wet Conditions

Travel Speed	PDO/Inj C Dist From NASS *	No. of Affected Crashes in CARDfile sample	CM Advisory Speed	No. of Crashes After CM **	Rounded Off
0 - 10	.80%	.02	23.49	.02	0
11 - 20	.00%	0	23.49	0	0
21 - 30	2.80%	.08	23.49	.08	0
31 - 40	5.30%	.16	32.45	.16	0
41 - 50	10.90%	.33	43.93	.33	0
51 - 60	22.50%	.68	53.79	.68	1
61 - 70	31.30%	.94	68.06	0	0
> 71	26.30%	.79	68.06	0	0
Total	100%	3		1.27	1

Icy/Snowy Conditions

Travel Speed	PDO/Inj C Dist From NASS *	No. of Affected Crashes in CARDfile sample	CM Advisory Speed	No. of Crashes After CM **	Rounded Off
0 - 10	.80%	.02	15.66	.02	0
11 - 20	.00%	0	15.66	0	0
21 - 30	2.80%	.08	15.66	0	0
31 - 40	5.30%	.16	21.63	0	0
41 - 50	10.90%	.33	29.29	0	0
51 - 60	22.50%	.68	35.86	0	0
61 - 70	31.30%	.94	45.37	0	0
> 71	26.30%	.79	45.37	0	0
Total	100%	3		.02	0

* Speed distribution from run-off-the-road accidents in NASS file.

** It is assumed that if the vehicle is traveling at a speed greater than the CM advisory speed, the driver will slow down and the accident does not occur.

APPENDIX J.

Table 96. Generic method worksheet impaired driver countermeasure.

	NT			NQ		
	PDO/Inj C	Injury	Fatal	PDO/Inj C	Injury	Fatal
ROR	22814	8548	347	4818	3160	189
Ped/cyclist	7861	3076	175	123	135	26
Crossing	18191	4183	99	728	389	22
Left turn	8825	2452	40	395	232	9
Rear-end	34729	4035	36	1956	622	13
Head-on	4994	1858	195	558	440	71
Total	97414	24152	892	8578	4978	330

	(NQ/NT)**2			No. Reduc.			
	PDO/Inj C	Injury	Fatal	PDO/Inj C	Injury	Fatal	Total
ROR	.04460	.13666	.29666	1017.49	1168.18	102.94	2288.62
Ped/cyclist	.00024	.00193	.02207	1.92	5.92	3.86	11.71
Crossing	.00160	.00865	.04938	29.13	36.18	4.89	70.20
Left turn	.00200	.00895	.05063	17.68	21.95	2.03	41.66
Rear-end	.00317	.02376	.13040	110.17	95.88	4.69	210.74
Head-on	.01248	.05608	.13257	62.35	104.20	25.85	192.40
Total				1238.75	1432.31	144.26	2815.32

Reduction in number of crashes: 1.33 percent.

Cost-Savings Crash Type	PDO/Inj C	Injury A & B	Fatals	Total
Run-off-the-road	$6,448,881	$200,353,331	$271,857,090	$478,659,302
Pedestrian/cyclist	10,404	508,641	9,272,267	9,791,312
Crossing paths	274,359	7,652,256	13,273,245	21,199,860
Left turn	108,512	4,524,070	5,474,069	10,178,650
Rear-end	1,059,241	17,895,710	11,781,981	30,736,931
Head-on	620,047	22,999,117	79,241,935	102,861,099
Total	$8,593,444	$253,933,124	$390,900,587	$653,427,155

Reduction in cost of all crashes: 5.69 percent.

Table 97. Generic method worksheet vision enhancement countermeasure.

	NT			NQ		
	PDO/Inj C	Injury	Fatal	PDO/Inj C	Injury	Fatal
ROR	22814	8548	347	8561	3535	188
Ped/cyclist	7861	3076	175	4235	406	62
Crossing	18191	4183	99	1195	368	26
Left turn	8825	2452	40	702	227	8
Rear-end	34729	4035	36	3422	592	14
Head-on	4994	1858	195	869	392	68
Total	97414	24152	892	18984	5520	366

	(NQ/NT)**2			No. Reduc.			
	PDO/Inj C	Injury	Fatal	PDO/Inj C	Injury	Fatal	Total
ROR	.14081	.17102	.29353	3212.53	1461.89	101.86	4776.28
Ped/cyclist	.29024	.01742	.12552	2281.54	53.59	21.97	2357.10
Crossing	.00432	.00774	.06897	78.50	32.37	6.83	117.70
Left turn	.00633	.00857	.04000	55.84	21.02	1.60	78.46
Rear-end	.00971	.02153	.15123	337.18	86.86	5.44	429.49
Head-on	.03028	.04451	.12160	151.21	82.70	23.71	257.63
Total				6116.82	1738.43	161.41	8016.65

Reduction in number of crashes: 3.78 percent.

Cost-Savings

Crash Type	PDO/Inj C	Injury A & B	Fatals	Total
Run-off-the-road	$20,361,032	$250,727,077	$268,987,906	$540,076,015
Pedestrian/cyclist	12,334,032	4,600,403	52,725,732	69,660,167
Crossing paths	739,251	6,848,349	18,538,665	26,126,265
Left turn	570,145	4,331,168	4,325,190	9,226,503
Rear-end	3,242,030	16,211,066	13,664,309	33,117,405
Head-on	1,503,820	18,254,837	72,686,909	92,445,565
Total	$38,750,310	$300,972,900	$430,928,710	$770,651,920

Reduction in cost of all crashes: 6.17 percent.

Table 98. Generic method worksheet low-friction warning countermeasure.

	NT			NQ		
	PDO/Inj C	Injury	Fatal	PDO/Inj C	Injury	Fatal
ROR	22814	8548	347	6721	1580	38
Ped/cyclist	7861	3076	175	435	92	9
Crossing	18191	4183	99	1313	540	2
Left turn	8825	2452	40	299	51	0
Rear-end	34729	4035	36	4490	431	0
Head-on	4994	1858	195	1436	429	27
Total	97414	24152	892	14694	3123	76

	(NQ/NT)**2			No. Reduc.			
	PDO/Inj C	Injury	Fatal	PDO/Inj C	Injury	Fatal	Total
ROR	.08679	.03417	.01199	1980.01	292.04	4.16	2276.21
Ped/cyclist	.00306	.00089	.00264	24.07	2.75	.46	27.29
Crossing	.00521	.01667	.00041	94.77	69.71	.04	164.52
Left turn	.00115	.00043	0	10.13	1.06	0	11.19
Rear-end	.01672	.01141	0	580.50	46.04	0	626.53
Head-on	.08268	.05331	.01917	412.91	99.05	3.74	515.71
Total				3102.39	510.66	8.40	3621.45

Reduction in number of crashes: 1.71 percent.

Cost-Savings

Crash Type	PDO/Inj C	Injury A & B	Fatals	Total
Run-off-the-road	$12,549,274	$50,088,333	$10,989,660	$73,627,266
Pedestrian/cyclist	130,130	136,222	1,111,026	1,477,377
Crossing paths	892,453	14,746,121	109,696	15,748,270
Left turn	103,432	218,622	0	322,054
Rear-end	5,581,484	8,592,563	0	14,174,047
Head-on	4,106,437	21,863,536	11,459,506	37,429,479
Total	$23,363,209	$95,745,395	$23,669,888	$142,778,493

Reduction in cost of all crashes: 1.24 percent.

Table 99. Worksheet for estimating potential savings by the generic method.

CM	Crash/Sev	NT	NQ	(NQ/NT)**2	Number Saved	Cost-Savings
CM5	ROR-PDO	22,768	17,957	.62204	14,162.59	$89,762,495.39
	ROR-Inj	8,535	5,380	.39734	3,391.26	581,631,528.95
	ROR-Fatal	340	158	.21595	73.42	193,901,775.85
CM5 Total		31,643	23,495		17,627.27	$865,295,800.19
% all					8.32%	7.54%
CM6	ROR-PDO	22,768	17,957	.62204	14,162.59	$89,762,495.39
	ROR-Inj	8,535	5,380	.39734	3,391.26	581,631,528.95
	ROR-Fatal	340	158	.21595	73.42	193,901,775.85
CM6 Total		31,643	23,495		17,627.27	$865,295,800.19
% all					8.32%	7.54%
CM7	ROR-PDO	22,768	4645	.04162	947.65	$6,006,186.16
	ROR-Inj	8,535	1556	.03324	283.67	48,652,210.22
	ROR-Fatal	340	48	.01993	6.78	17,895,757.55
CM7 Total		31,643	6,249		1,238.09	$72,554,153.93
% all					.58%	.63%
CM8	Ped-PDO	7861	7738	.96895	7,616.92	$41,177,094.19
	Ped-Inj	3076	2941	.91415	2,811.92	241,398,129.03
	Ped-Fatal	172	146	.72052	123.93	297,477,792.67
CM8 Total		11,109	10,825		10,552.78	$580,053,015.90
% all					4.98%	5.05%
CM10/11	Rear-PDO	34729	32773	.89053	30,927.17	$297,364,695.83
	Rear-Inj	4035	3413	.71546	2,886.88	538,816,323.14
	Rear-Fatal	36	23	.40818	14.69	36,879,690.53
CM10/11 Total		38,800	36,209		33,828.74	$873,060,709.49
% all					15.97%	7.60%
CM12/13	Head-on-PDO	4994	1514	.09191	458.99	$4,564,655.43
	Head-on-Inj	1858	585	.09913	184.19	40,655,335.37
	Head-on-Fatal	195	58	.08847	17.25	52,880,354.87
CM12/13 Total		7,047	2,157		660.43	$98,100,345.68
% all					.31%	.85%

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