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Examination of Single Vehicle Roadway Departure Crashes and Potential IVHS Countermeasures

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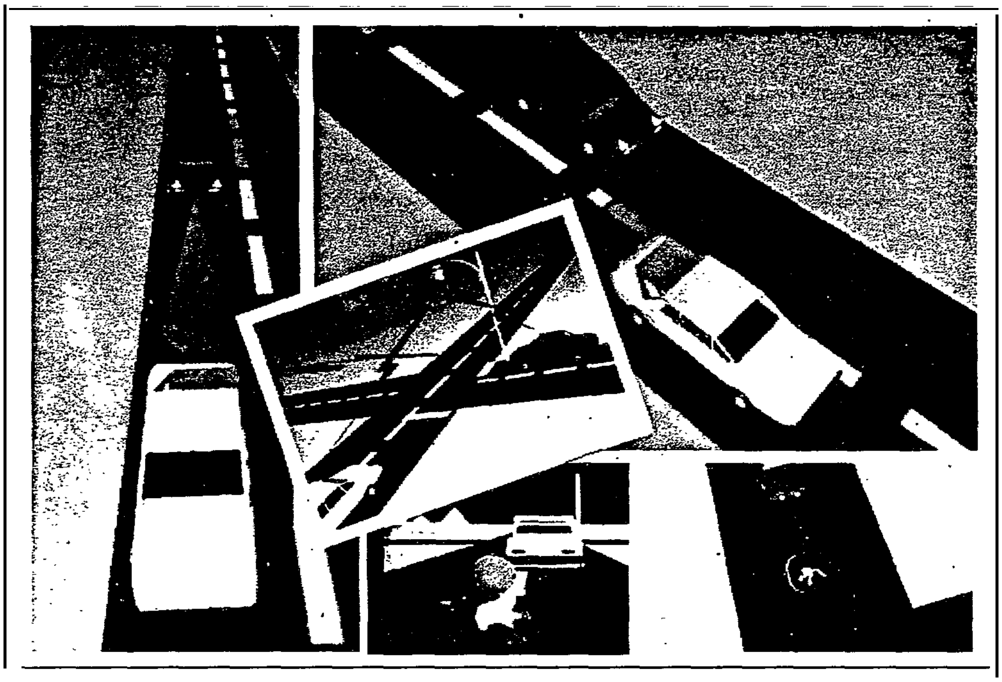

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13. ABSTRACT (Maximum 200 words)

This report provides an analysis of single vehicle roadway departure (SVRD) crashes to guide the development of Intelligent Vehicle Highway Systems (IVHS) crash avoidance systems. It introduces the problem of SVRD crashes: A crash is defined as a SVRD when the first harmful event is the departure from the roadway, thus excluding departures resulting from prior impacts. Two crash subtypes are identified and causal factors that contribute to SVRD crashes are assessed clinically from a sample of SVRD crashes. From these data, functional goals for IVHS SVRD crash avoidance systems are described. Three simple models of potential kinematic remedies to pre-crash scenarios are examined: stopping the vehicle, steering to return to the original travel lane, and slowing the vehicle to a safer speed. These models illustrate the distances and time's needed to prevent crashes. The report concludes with a discussion of key research needed to extend the analysis presented.

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Single Vehicle Roadway Departures, Run-Off-The-Road, Kinematic Modelling, Crash Avoidance, Countermeasures, Intelligent Vehicle Highway System (IVHS), Crash Causes

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PREFACE

The National Highway Traffic Safety Administration (NHTSA) Office of Crash Avoidance Research (OCAR), in conjunction with the Research and Special Programs Administration (RSPA) Volpe National Transportation Systems Center (VNTSC), has a multidisciplinary program underway to: identify crash causal factors and applicable Intelligent Vehicle Highway Systems (IVHS) countermeasure concepts; model crash scenarios and avoidance maneuvers; provide preliminary estimates of countermeasure effectiveness when appropriate; and identify research data needs.

Under this program major target crash types will be examined, namely:

- Rear-End
- Backing
- Single Vehicle Roadway Departures
- Lane Change/Merge
- Intersection/Crossing Path
- Reduced Visibility (Night/Inclement Weather)
- Opposite Direction

This report presents the results of the single vehicle roadway departure study. The results are based on 100 hard copy reports selected from the 1991 Crashworthiness Data System (CDS), and from the 1991 General Estimates System (GES), both within the National Accident Sampling System (NASS). The crashes used in the clinical analysis were weighted for severity so that they might more closely approximate the national profile.

John S. Hitz, Joseph S. Koziol Jr., and Wassim G. Najm of VNTSC; and William A. Leasure, Jr., August L. Burgett, Ronald R. Knipling, Lloyd Emery and Jing S. Wang of NHTSA OCAR provided technical guidance and reviewed the report.

The project contractor (Contract No; DTRS-50189-D00086) is Battelle Memorial Institute, with the major involvement of subcontractor ARVIN/Calspan This present document is based in part on contractor analyses of SVRD crashes, including SVRD crash causal factor analyses, crash reconstructions, and identification of applicable countermeasure concepts.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd ❑ 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2 = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2 = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (Lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp ❑ 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] ^{o}F ❑ y ^{o}C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliters (ml) ❑ 0.03 fluid ounce (fl oz)
1 liter (1) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] ^{o}C ❑ x ^{o}F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES: 0 1 2 3 4 5 6 7 8 9 10

CENTIMETERS: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 25.40

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. Cl3 10286.

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ABBREVIATIONS AND ACRONYMS

The following list contains abbreviations and acronyms used in this report, together with their definitions.

a	Braking level (rear-end collision model)
a	Lateral acceleration (lane return model)
a_{MAX}	Maximum lateral acceleration
CDS	Crashworthiness Data System
D_{LAT}	Lateral distance travelled by the vehicle
D_{SLOW}	Distance required to slow vehicle from travel velocity to desired velocity
D_{STOP}	Distance required to bring vehicle to a complete stop
FARS	Fatal Accident Reporting System
GES	General Estimates System
g	Unit force of gravity, 32.2 ft/s^2
IVHS	Intelligent Vehicle Highway Systems
k	Rate of change of lateral acceleration
NASS	National Accident. Sampling System
NHTSA	National Highway Traffic Safety Administration
OCAR	Office of Crash Avoidance Research
PR	Police Reported
SVRD	Single Vehicle Roadway Departure
t	Time since lateral acceleration was first applied
t_{CRIT}	Time required to reach maximum lateral acceleration
t_R	Time between start of event and onset of corrective action
V_0	Initial travel velocity
V_F	Desired final velocity
V_{lat}	Lateral Velocity
VMT	Vehicle-Miles Travelled
e	Departure angle

EXECUTIVE SUMMARY

The single vehicle roadway departure (SVRD) crash type was analyzed in this report. Types of SVRD crashes were described and the size of the crash problem was estimated from national data bases. In 1991, SVRD crashes accounted for 21 percent of all police reported crashes, and 37 percent of all fatalities.

SVRD crash circumstances were analyzed from 100 crash reports in the NASS CDS data file to classify the crashes into subtypes, and to reveal the factors that were involved in causing them. From these analyses, the evasive and non-evasive subtypes emerged. Evasive crashes are those where the driver attempts, to avoid impacting a pedestrian, animal or another vehicle and as a result of his maneuver leaves the roadway. These account for 21% of SVRD crashes. Non-evasive crashes are the remaining 79% which did not involve such prior maneuvering. Approximately 61% of SVRD crashes occurred on curves. Of these, 62% were off the right side of the road.

The causal factor analysis did not reveal one dominant cause but rather several factors of nearly equal importance. These included excessive speed, losing directional control, inattention to lane tracking, driver relinquishing control, and evasive maneuvers. Excessive speed, which accounted for 20.1% of the cases, generally involved speeding on curves. Losing directional control (20.3%) involved loss of maneuvering ability on wet, snowy or icy roadways. In the cases determined to be caused by driver inattention to lane tracking (8.5%), the driver allowed the vehicle to drift out of its travel lane. In 25.4% of the cases, the driver relinquished steering control through such factors as high levels of intoxication,. falling asleep and physical illness (e.g., seizures). Finally, 20.7% of the cases involved an evasive maneuver, generally precipitated by inattention on the part of either the driver of the subject vehicle or by that of the principal other vehicle.

Based on an examination of these causal factors and crash subtypes, nine countermeasure concepts were identified which could be useful in preventing SVRD crashes. Two of these would directly address the driver's status ("driver vigilance monitor" and "driver intoxication monitor) while the "vehicle component monitor" would address the vehicle's status. Based on the road surface conditions and/or the road geometry, the "pavement condition monitor" and the "speed reduction. system" would help ensure that the vehicle speed is not excessive. A "lane keeping system" would keep a vehicle from departing its lane through warnings or automatic action. An "object detection/rear end collision prevention system" would detect a pedestrian, obstacle, animal or another vehicle in the subject vehicle's path and issue a warning or automatically brake to avoid the hazard. The complex "evasive action system" would assess the pre-crash environment and determine the most effective action to take. Finally, the driver's ability to see in darkness or bad weather can be improved by a "vision enhancement system".

To better understand the kinematics and crash. avoidance potential of SVRD crashes, mathematical models were derived for three kinematic remedies. These were the rear-end collision, the lane return, and the speed reduction model. By exercising each model under various conditions of SVRD crash scenario parameters, the critical distances and times for each scenario were illustrated. These relationships will be useful for designers of IVHS crash avoidance technologies as they begin to develop concepts for new systems, and will give the IVHS community a tactical view of how SVRD crashes can be avoided.

The need for further research was described in several areas: developing better estimates of the crash problem size, increasing the robustness of the clinical analysis, specific concerns for the three kinematic subtypes, and additional qualitative data needs.

1. BACKGROUND

1.1 INTRODUCTION

With the recent advancements in computer, communication, sensor and actuator technologies, Intelligent Vehicle-Highway Systems (IVHS) offer the potential to improve highway safety by avoiding crashes or mitigating their severity. The primary purpose of this report is to examine the potential impact that IVHS countermeasures could have on Single Vehicle Roadway Departure (SVRD) crashes. This is one in a series of studies sponsored by the National Highway Traffic Safety Administration's (NHTSA) Office of Crash Avoidance Research (OCAR) in conjunction with the Volpe National Transportation Systems Center (VNTSC) that focuses on specific crash types or causes. The rationale for this approach is that distinct IVHS countermeasure concepts are applicable to the various crash types or causes.

This report thus provides an analysis of SVRD crashes to guide the development of IVHS crash avoidance systems. It describes the size of the SVRD crash problem. Crashes are categorized into evasive and non-evasive scenarios. Evasive crashes are those where the driver attempts to avoid impacting a pedestrian, animal or another vehicle and as a result of his maneuver leaves the roadway. These account for 21% of SVRD crashes. Non-evasive crashes are the remaining 79% which did not involve such prior maneuvering. Causal factors which contribute to SVRD crashes are derived from clinical assessment of a sample of these crashes. From these results, functional goals for IVHS SVRD crash avoidance systems are described. Simple kinematic models of crash avoidance requirements are presented to outline the space of time and distance available for crash avoidance. The report concludes with a discussion of research needed to extend the analysis presented here including the parameters and data needed to model crash scenarios and driving behavior so that estimates of effectiveness of potential countermeasures can be made.

1.2 DEFINITION OF SINGLE VEHICLE ROADWAY DEPARTURES

In this report, "single vehicle roadway departure" refers to those crashes where the first harmful event is the vehicle leaving the roadway. It does not include crashes where roadway departure results from a collision with another vehicle, although SVRD crashes can be caused by a maneuver initiated by a driver trying to avoid another vehicle. These departures may be off either edge of the road or onto the center median of a divided highway.

1.3 PRELIMINARY NATURE OF THIS WORK

The primary methodology of this study is analytical rather than empirical. It employs reviews of existing accident data, available information on driver/vehicle performance, and basic laws of physical motion. The models described have been constructed from basic parameters of vehicle motion and describe possible interventions to change that motion as required to prevent crashes (e.g., a warning or automatic control to reduce speed). This presentation of SVRD crash modeling is intended to be heuristic, supporting multiple iterations of the modeling using empirical data on system, vehicle and human parameters. Such data may be obtained through additional accident data analysis and/or driver performance research using state-of-the-art research tools such as the advanced driving simulator or instrumented vehicles.

In particular, one NHTSA-sponsored research program currently underway will greatly extend the preliminary concepts and modeling presented in this report. This is the Single Vehicle Roadway Departure Performance Specification Development program being performed under NHTSA contract DTNH22-93-C-07023. This program will extend the formulations of this and other preliminary analyses into countermeasure performance specifications; i.e., recommended functional guidelines for optimal countermeasure performance and effectiveness. These performance specifications will facilitate industry efforts to develop practical, driver-friendly, and commercially-viable SVRD crash countermeasure systems.

2. PROBLEM SIZE

Table 2-l presents the SVRD crash problem sizestatistics for all vehicle types and combination-unit trucks. The statistics, which are derived from the 1991 General Estimates System (GES) and the Fatal Accident Reporting System (FARS), show:

- In 1991, there were over 1.27 million police reported (PR) SVRD crashes with 15,533 associated fatalities.

- SVRD crashes represented approximately 20.8 percent of all PR crashes and 37.4 percent of all crash fatalities.

- The expected number of involvements over a vehicle's life is two and a half times greater for combination unit trucks than for passenger cars. **A** combination truck can be expected to be involved in 0.23 SVRD crashes during its operational life, compared to 0.09 for a passenger vehicle.

- Motorcycles have much higher rates of invdlvement per vehicle mile travelled than do other vehicle types. Their rate was 205.2 involvements per 100 Million VMT compared to 59.8 for passenger vehicles and 24.2 for combination-unit trucks. On the other hand, the relatively low exposure mileage of motorcycles means they are actually less likely to be involved in these crashes over their operational lives than are passenger vehicles and combination-unit trucks.

- The 1.27 million PR SVRD crashes included an estimated 550,000 right side roadway departures, 368,000 left side roadway departures, and 348,000 "forward impacts". "Forward impacts" included primarily collisions with parked vehicles (315,000) and end departures (26,000).

- SVRD crashes causedapproximately 16.5 percent of all Crash-caused congestion or delay.

- There are an estimated 1.58 million non-police reported SVRD crashes annually in addition to PR SVRD crashes. Therefore, there were approximately 2.85 million total SVRD crashes in 1991.

The reader is referred to Wang and Knipling (1994) for more details on the derivation of these statistics and for statistical information on the conditions of occurrences of SVRD crashes.

Table 2-l..

Problem Size Estimate: Single Vehicle Roadway Departure Crashes

(From Wang and Knipling, 1994)

GES-Based Statistics (1991)		All Vehicles	Pass. Veh.	C. U. T.	S. U.T.	Motorcycles
Annual # PR Crashes	Total:	1,269,000	1,200,000	25,000	16,000	19,000
(GES)	Injury:	441,000	417,000	5,000	3,000	14,000
	PDO:	828,000	782,000	21,000	13,000	5,000
Annual # Fatalities (FARS)		15,533	13,862	306	81	1,052
Annual # Non-Fatal	Total:	574,000	544,000	5,000	4,000	15,000
Police Reported	A:	121,000	112,000	1,000	1,000	6,000
Injuries (GES)	B:	234,000	221,000	2,000	1,000	8,000
	C:	218,000	211,000	1,000	2,000	2,000
% of all PR Crashes		20.8%	20.1%	13.5%	12.4%	18.3%
% of all FCE		30.7%	29.6%	10.5%	9.9%	29.3%
% of all Fatalities		37.4%	36.3%	8.4%	7.0%	35.9%
Annual Involvements:						
Involvement Rate Per 100 Million VMT		58.4	59.8	26.2	29.9	205.2
Involvement Rate Per 1,000 Registered Vehicles		6.59	6.60	15.85	3.78	4.51
Expected Involvements During Vehicle Life		0.0865	0.0858	0.2330	0.0556	0.0338
Estimated Annual NPR Crashes	Total:	1,580,000	1,492,000	40,000	25,000	9,000
Estimated Total Annual Target Crashes (PR+NPR)	Total:	2,849,000	2,692,000	65,000	41,000	28,000
Crash-Caused Congestion (Delay)	VehHrs	74,300,000	70,600,000	2,100,000	700,000	600,000
% of All Crash-Caused Delay		16.5%	15.69%	0.47%	0.16%	0.14%

Legend:

A:	Incapacitating Injuries	NPR:	Non-Police Reported
B:	Nonincapacitating Injuries	PDO:	Property Damage Only
c :	Possible Injuries	PR:	Police Reported
C.U.T.:	Combination Unit Trucks	S.U.T.:	Single Unit Trucks
FARS:	Fatal Accident Reporting System	VMT:	Vehicle Miles Traveled
GES:	General Estimates System		

3. ANALYSIS OF CRASH CIRCUMSTANCES

3.1 INTRODUCTION

Details about SVRD crash scenarios and causes are needed to develop a full understanding of how these crashes can be prevented. The accident data shown in the previous chapter are insufficient for determining the actual cause of the crash. Accident files such as GES and FARS provide information on crash problem size and conditions of occurrence but do not provide detailed investigative, information on specific crash causes such as specific driver errors.

Therefore, the statistical data have been supplemented by a "clinical analysis". This involves a careful examination of detailed accident reports compiled as part of the National Accident Sampling System (NASS) program's Crashworthiness Data System (CDS). These reports include examination of the accident scene, police reports, and driver and witness interviews. An experienced accident reconstructionist uses this information to determine the cause of the accident. These data, when supplemented by the GES results create a detailed picture of the crash circumstances.

This chapter describes the analysis sequence for this crash type, related decision points, and the results of the causal. factor analysis.

For further analysis and integration of the causal factor data from this and several other crash . types, see (Najm et al., 1994).

3.2 SELECTION OF CLINICAL CASE SAMPLE

The initial case listing identified all SVRD crashes available in the 1991 NASS CDS data file residing at Calspan, a Zone Center in the NASS CDS Program. A sample of 100 cases. was then selected from this listing.

Checks performed after the selection indicated that the accident and injury severity profile of the final sample was more severe than the GES profile. This was expected since the NASS CDS System oversamples more severe cases. To align the severity distribution of the clinical sample with the severity distribution of the GES, weighted samples were created for the clinical data. Case weights used to correct clinical samples were proportional to the percentage of the national severity level (determined from the GES file) divided by the percentage of cases in the clinical sample. In-the weighted sample, lower severity level cases were assigned higher sampling weights than the more severe cases. See Appendix A for further details on the case weighting scheme.

3.3 CLINICAL ANALYSIS PROCEDURE

The NASS CDS hard copy case reports were reviewed to determine the major events and causal factors associated with each crash. The case elements essential to the analysis were:

- Police reports
- Driver statements
- Witness statements (where available)
- Scaled schematics depicting crash events and physical evidence generated during the crash sequence
- Case slides documenting the physical plant, physical evidence,. and damage sustained by case vehicles

Written summaries delineated the circumstances surrounding the crash, driver actions, impact events, and causal factors associated with impact events. There was also interest in accumulating crash descriptions for subsequent identification of trends in crash circumstances, For example, summaries were used to determine if there were crash subtypes within the SVRD crash category and if there were key or critical relationships within crash subtypes.

The clinical analysis conducted for this effort was an independent assessment of available information. These inputs were evaluated against the physical evidence generated by crash events and in the total context of the accident environment. In several instances, the interpretation of crash events and contributory causal factors differed from police reported information.

3.4 CLINICAL ANALYSIS RESULTS

Results reported here are based on the clinical sample of 100 cases.

3.4.1 Crash Circumstances

Review of the crash summaries generated for this effort provided distinctive insight to the circumstances surrounding SVRD crashes. Major findings may be summarized as follows:

- Roadway alignment and roadway surface condition characteristics play a significant role in SVRD crashes.

- Crash circumstances within the SVRD crash problem include a combination of physical crash characteristics, such as vehicle failures; and causal factors, such as drivers being intoxicated or falling asleep. Six major crash circumstances were identified within the selected clinical sample and are shown in Table 3-1.

Table 3-l.
Single Vehicle Roadway Departure
Causal Factor Analysis
(Weighted Percentages)

Causal Factor	Curve	Straight	Weighted Case Total	% Total
Lost Directional Control on Road Surface:				
Snow/Ice	9.9	6.3	16.2	
Wet	4.1		4.1	
SUBTOTAL				20.3
Driver inattentive to **Lane** Tracking:				
Drifted off roadway or out of travel lane	6.4	0.4	6.8	
Steered off roadway while retrieving fallen object	1.3	0.4	1.7	
SUBTOTAL				8.5
Evasive maneuver (steered off roadway)				
To avoid animal or pedestrian crossing roadway	0.4	5.4	5.8	
Vehicle encroaching into travel lane				
Opposite travel directions	4.1	1.8	6.5	
Same travel direction	1.4		1.4	
Steered off roadway to avoid vehicle traveling in same direction (Situation precipitated hy driver inattention)				
Lead vehicle **moving** (LVM)	1.4	1.4	2.8	
Lead vehicle stopped (LVS)		4.2	4.2	
SUBTOTAL				20.7
Driver relinquished steering contml:				
Intoxicated	7.9	2.2	10.1	
Physical (seizure, passed out, etc.)	1.3	2.2	3.5	
Fell asleep	3.4	8.4	11.8	
SUBTOTAL				25.4
Vehicle failure:				
Tire blowout	2.2	2.2	4.4	
Engine stalled	0.9		0.9	
SUBTOTAL				5.3
Vehicle speed:				
Excessive speed	5.4		5.4	
Vehicle speed and alcohol consumption	3.9		3.9	
Vehicle speed and driver inexperience:	3.1	1.4	4.5	
Attempted to initiate 90^0 turn	1.4	2.7	4.1	
Unsafe driving act primarily vehicle spted)	2.2		2.2	
SUBTOTAL				20.1
TOTAL	61.3	39.0	100.3	100.3

3.4.2 Causal Factors

The statistics shown in Table 3-l represent the causal factor percentages of the total SVRD case sample. No single causal factor predominates. In the clinical sample, 20 percent of the crashes involved loss of directional control on road surfaces degraded by environmental conditions, 9 percent involved driver. inattention to lane tracking, 21 percent involved an intentional evasive maneuver initiated by the driver, 25 percent involved the driver relinquishing steering control, 5 percent involved vehicle failures, and 20 percent involved excessive vehicle speed.

38 percent of the evasive maneuver cases occurred when the driver initiated an evasive maneuver to avoid a vehicle encroaching into the travel lane, while 34 percent involved an unsuccessful rear-end crash avoidance maneuver. The driver approached a lead vehicle from the rear. Rather than braking and striking the lead vehicle, the driver steered (typically to the right) to avoid the lead vehicle, left the roadway, and hit roadside appurtenances.

Scenarios. involving vehicle speed as a primary or contributing causal factor were typically associated with curves (79 percent of vehicle speed cases) or the situation where the driver attempted to initiate a very sharp turn (13 percent).

In 62 percent of the cases the vehicle departed the right side of the road. This higher proportion is expected for the following reasons:

- In situations involving curves to the right (departure to the left), there is an additional travel lane or median strip available to the driver where a recovery can be completed and the departure prevented.

- When the roadway curves to the right, there is increased potential for the subject vehicle to become involved with opposing traffic, resulting in a two vehicle collision rather than a single vehicle roadway departure crash.

The next chapter will use these results, along with those fromchapter 2, and postulate some concepts to prevent these collisions.

4. COUNTERMEASURE CONCEPTS

4.1 INTRODUCTION

The previous chapter provided data on the scenarios and primary causes of SVRD crashes. This information can help determine what actions might help prevent the crashes, and thus the potential countermeasures.

The time framework under which these countermeasures must function is illustrated in Figure 4-1, a time-intensity graph of crash avoidance requirements (NHTSA, 1992). As time runs out, normal driving gives way to some opportunity for driver alerts and warnings to which the driver may react. As available time shortens, driver assistance in the form of driver-vehicle control intervention is necessary. As available time shortens even further, driver delays or inadequate braking are not tolerable and a fully automatic control system must come into play. Sometimes, even these systems may not be effective if the kinematics of the situation are too demanding. As NHTSA (1992) pointed out:

As indicated in the figure, the characteristics of a given crash avoidance system will depend largely on the crash scenario itself, i.e., the time available to take evasive action and the intensity of action needed to avoid the crash.

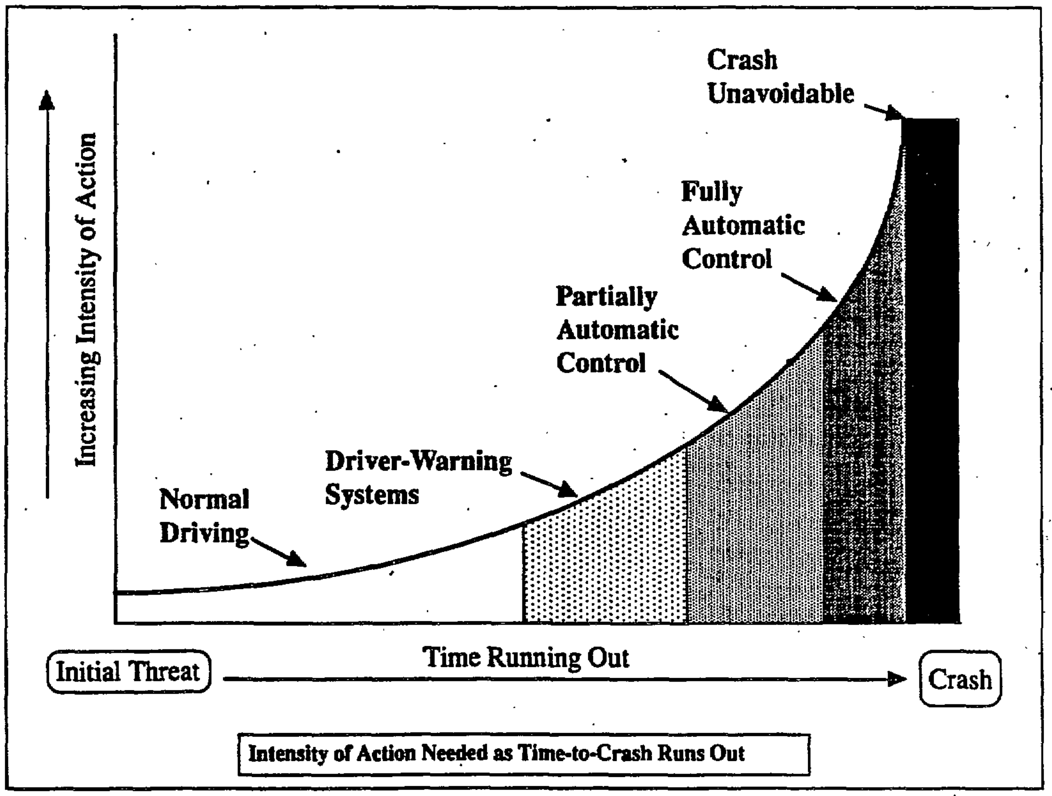


Figure 4-1. Time-intensity Graph of Crash Avoidance Requirements

4.2 FUNCTIONAL DESCRIPTION OF CONCEPTS

The results of the causal factor analysis in Chapter 3 were regrouped into two subtypes: (1) evasive maneuvers, i.e., any SVRD crashes caused by the driver's attempts to avoid another vehicle, pedestrian or animal, and (2), non-evasive maneuvers. These two groups lead to a different set of countermeasure concepts. Table 4-l outlines which countermeasure concepts are applicable to which causal factors and crash subtypes. These are functional concepts, rather than technology-specific devices. There are many different possible technological implementations of these countermeasures, but the overall functional requirements are similar. While this list is broad, other countermeasure concepts may also be effective.

A brief functional description of each countermeasure concept and a discussion of its applicability to selected causal factors follows:

4.2.1 Driver Vigilance Monitor

This would detect an non-vigilant driver (generally due to drowsiness), either through direct observation (e.g., eyelid closure rate) or through performance monitoring (e.g., steering, inputs). The driver would be advised of his condition before an event develops. (Dingus et al., 1987; Knipling and Wierwille, 1993) This would be applied at the far left side of the time-intensity chart, before the dangerous scenario develops.

Drowsy Driver: Drivers who are drowsy would benefit the most from this system. The early detection of drowsiness is crucial, as is the driver's response to an alarm.

Inattentive Driver: Inattentive drivers 'may display some traits similar to those of drowsy drivers. While some causes of inattention are not likely to be amenable to this countermeasure (e.g., retrieving dropped object, or attending to child in back seat), others (e.g., daydreaming) could well be.

Intoxicated Driver: Drivers operating under the influence of alcohol could also exhibit behavior similar **to** drowsy drivers. Driver responsiveness to such a system, however, would probably be limited because of their impaired conditions.

4.2.2 Evasive Action System

This system would automatically take or advise on an appropriate evasive maneuver based on consideration of a complex dynamic situation (e.g., encroachment by a vehicle travelling the' opposite direction). It would require extensive knowledge of the entire driving environment. This would act at the far right of the time-intensity chart, where extreme measures are called for.

Encroachment. Same and Opposite Direction: The system would be required to operate on both vehicles. The levels of sensing, computing, communication and control required would be extremely demanding.

Table 4-l. Countermeasure Concepts by Causal Factor (with percentages of clinical sample) and Crash Subtype

Counter-measure Concepts	Evasive Maneuvers				Non-evasive Maneuvers						
	Animal/ Pedestrian (5.8%)	Encroach-Same Direction (1.4%)	Encroach-Opposite Direction (6.5%)	Rear-End Crash Avoidance (6.9%)	Drowsy Driver (11.8%)	Excessive Speed (20.0%)	Inattentive Driver (8.5%)	Intoxicated Driver (10.1%)	Lost Direc Control (20.2%)	Physically Incapacit. (3.5%)	Vehicle Failure (5.2%)
Driver Vigilance Monitor					X		X	X			
Evasive Action		X	X	X							
Intoxic. Driver Monitor								X			
Lane Keeping		X*	X*		X		X	X		X	
Obj Det/ Rear-End Prevent	X	X		X							
Pavement Condition Monitor									X		
Speed Reduction						X	X		X		
Vehicle Compon. Monitor											X
Vision Enhance	X										

* to be used on the encroaching vehicle

Rear-End Crash Avoidance: The system need only be on the following vehicle. If braking is all that is required, this becomes the equivalent of the object detection system described in section 4.2.5. If steering is necessary to prevent the collision, however, the system would have to perform the complex function of automatically maneuvering around a lead vehicle while maintaining control and avoiding either a roadway departure or a head on collision.

4.2.3 Intoxicated Driver Monitor

This system would detect a drunk driver through such methods as physiology or driving performance, and either advise him/her, disable the vehicle and/or advise authorities. This would be applied at the far left side of the time-intensity chart, before the dangerous scenario develops,

Intoxicated Driver: Determining the unsafe level of impairment may be challenging. Complicating the issue further are the considerable variation in different drivers'. physiology and performance for identical levels of intoxication. Additionally, the level of compliance for "voluntary systems" may be low. However, since a large percentage of crashes are alcohol-related, any improvement would be beneficial.

4.2.4 Lane Keeping System

This system would detect lane departure (or impending lane departure) and either automatically correct the drift or advise the driver to take action. This would operate in the middle to right side of the time-intensity chart, and is crash type specific. See Section 5.3 for an examination of the kinematics of correcting lane departures.

Encroachment. Same Direction: In this case, the system, installed on the encroaching vehicle, would prevent that vehicle from drifting from its original travel lane, thus eliminating the need for the evasive action which resulted in the roadway departure. This could also prevent lane change crashes where the SV does not initiate an evasive maneuver.

Encroachment, Opposite Direction: Again, the system, installed on the encroaching vehicle, would prevent the vehicle from entering the SV's travel lane and precipitating the need for an evasive maneuver. This would also be effective in preventing head-on collisions.

Drowsy Driver: Drowsy drivers could certainly benefit from an automatic system. Lane tracking may be a component of a driver status monitor, which' would issue a warning before a driver falls asleep. Rumble strips which alert drifting drivers also appear effective.

Inattentive Driver: An automatic system would be effective for an inattentive driver. A warning system would be of some use, depending' on the level of distraction, and the speed and intensity of the driver's actions.

Intoxicated Driver: An intoxicated driver would also benefit from an automatic lane keeping system, however, higher levels of driver impairment will diminish a warning system's effectiveness.

Physically Incapacitated Driver: An incapacitated driver will be, by definition, unable to respond to a warning system. An automatic system could be helpful, however, further steps would have to be taken to prevent the incapacitated driver from striking a lead vehicle or being struck from behind.

4.2.5 Object Detection/Rear-End Collision Prevention System

This system would detect an impending rear-end collision based on dynamic properties of both vehicles and either automatically brake the vehicle or advise the driver to take appropriate action. (see Knipling et al., 1993). This would operate in the middle. to right section of the time-intensity chart, depending on system configuration, and is crash type specific.

Evasive Maneuvers to Prevent Striking Animal or Pedestrian: A system such as this could possibly prevent some roadway departures due to these maneuvers, as well as some crashes between cars and pedestrians or animals. However, most headway detection systems are not sensitive enough to detect pedestrians or animals in time to take the necessary action. Also, pedestrians and animals often enter the vehicle's 'intended path suddenly and close to the vehicle, allowing little time to brake or steer.

Evasive Maneuvers to Prevent Striking Vehicle Encroachment. Same Direction: In some cases, this system can alert the driver to the presence of another vehicle "cutting in," perhaps providing additional time in which to react. However, these maneuvers are often sudden, leaving little time to respond. Additionally, in all of these cases, the driver did swerve, leading to the SVRD, showing he was aware of the hazard.

Evasive Maneuvers to Prevent-Rear-End Crash: A headway detection system would provide additional time to safely slow or stop the SV to avoid striking a decelerating or stationary vehicle in the road ahead. A system of this sort appears quite promising (Knipling, 1993). Additional information is needed in regards to driver choice of braking versus steering.

4.2.6 Pavement Condition Monitor

This system would determine if the pavement friction were degraded due to weather effects, either at the current location or at some point ahead, and allow the driver to adjust his/her driving accordingly. This would operate on the left of the time-intensity chart, providing information to the driver.

Lost Directional Control on Wet or Icy Roadway: The system could be quite beneficial in these cases if the warning were issued in time for the driver to respond. Additional information is needed as to what maneuvers the drivers were performing when the vehicle lost control.

4.2.7 Speed Reduction System

This system would advisk that the speed for the current conditions and/or geography is too great and either automatically reduce it or advise the driver to decelerate to the recommended speed. This would operate in the middle of the time-intensity chart.

Excessive Speed: This factor is the most likely to benefit from a speed reduction system. Hdwever, the reasons for the excessive speedmust be understood. If the driver was already aware that the travel speed was potentially dangerous, a system would probably not be heeded. If instead the driver was unaware of an upcoming sharp turn, the system could be quite valuable.

Inattentive Driver: Inattentive drivers who are unaware of approaching curves or other hazards could benefit from a speed reduction system. The success depends largely on the degree of inattention and the time required to properly assess the situation.

Lost Directional Control on Wet or Icy Roadway: If the speed reduction system accounted for roadway conditions (essentially functioning as a pavement condition monitor), it could provide important advisories to drivers, preventing many of these crashes.

4.2.8 Vehicle Component Status Monitor

This system would monitor the condition of such critical systems as steering, braking, and tires, and warn the driver of impending failure. This would be applied at the far left side of the time-intensity chart, before the dangerous scenario develops.

Vehicle Component Failure: The success of the system would depend on the ability to detect, the hazard early enough to allow the driver to respond before the component fails. It is also critical that the driver believes in the credibility of the system, and takes action, even though there is no problem observable by the driver.

4.2.9 Vision Enhancement System

This system would enhance the driver's awareness of objects in or near his/her travel path, allowing him/her to determine appropriate action. Such a system could provide the driver with more reaction time for crash avoidance by generating imagks of potential hazards which are farther away than the driver can see. This would operate on the left side of the time-intensity chart.

Evasive Maneuvers to Prevent Striking Animal or Pedestrian: This system could alert the drive; to the presence of a pedestrian or animal in dark or other reduced visibility circumstances. Unlike the headway detection system, the driver could be made aware of the potential hazard before it enters the roadway, giving the driver considerably more time to stop.

The next chapter examines the kinematics of the possible crash avoidance maneuvers for 'certain crash circumstances. This information can help define the required functional ranges and the interrelationship of driving scenario parameters for many of these countermeasures and provide methods to estimate the effectiveness of these systems.

5. KINEMATIC MODELING

5.1 INTRODUCTION

This chapter presents several models of the crash scenarios and the most likely kinematic remedies to the crash subtypes. Table 5-l shows the various models that are most appropriate for each of the subtype/causal factor combinations. These do not model the countermeasures, but rather, the kinematic crash scenarios and remedies that are possible.

It is important to note that all these models are countermeasure and technology independent. No assumptions are made about how the determination to initiate action is made, nor whether the action will be performed by the driver or the vehicle. This is simply the physics describing the crash avoidance maneuvers.

The main purpose of the kinematic modeling in this report is to show and study the relationship between key variables (e.g., velocities, accelerations, and lateral and ldngitudinal distances) so that a determination can be made about the feasibility of applying a remedy as well as the bounds and accuracies of the variables associated with the remedy. As the modeling is extended; these variables can be related to overall benefits and costs (e.g., accidents or lives saved vs. false alarm rate or reduced roadway capacity). Policy makers can use this information to make decisions regarding the deployment of effective countermeasures. Designers can use both the information. from the early studies and results to provide a system with the necessary characteristics.

The following SVRD crash prevention scenarios are modeled:

- Rear-End Collision Prevention. This model examines the distance required to bring a vehicle to a stop.
- Lane Return. The distance required to stop. the lateral motion of a vehicle which is . departing its lane at a given angle is modeled.
- Speed Reduction. This model examines the distance needed to slow a vehicle from one speed to another.

5.2 REAR-END COLLISION PREVENTION MODEL

Several of the cases involve steering off the roadway to avoid hitting a vehicle, person, or animal on the road ahead. If the vehicle could be brought to a stop before it reached the obstacle, then no evasive maneuver would be needed. This model, expressed in Equation (1) determines the distance required for the vehicle to be brought to a stop. This same expression holds whether, for example, the driver recognizes the hazard and decides to

Table 5-1. Kinematic Remedies by Causal Factor (with percentages of clinical sample) and Crash Subtype

	Evasive Maneuvers				Non-evasive Maneuvers						
	Animal/ Pedestrian (5.8%)	Encroach-Same (1.4%)	Encroach-Opposite (6.5%)	Rear-End Avoidance (6.9%)	Drowsy Driver (11.8%)	Excessive Speed (20.0%)	Inattentive Driver (8.5%)	Intoxicated Driver (10.1%)	Lost Direc Control (20.2%)	Physically Incapacit. (3.5%)	Vehicle Failure (5.2%)
Rear-End Collision Prevention	X	X	X	X							
Lane Return					X		X	X			
Speed Reduction						X		X	X		
Vehicle/ Obstacle Avoidance Manuever*	X	X	X	X							

* Not modeled since extremely sensitive to particulars of scenario

brake, a driver learns of the hazard through-a warning system, or a system automatically applies the brakes. The only differences lie in the time delays and the braking levels.

$$D_{STOP}=V_0 t_R+\frac{V_0^2}{2a} \tag{1}$$

where

D_{STOP}	=	distance required to stop
V_0	=	initial velocity
t_R	=	total time delay before vehicle begins braking
a	=	constant deceleration level of the vehicle

The first term ($V_0 t_R$) determines the distance travelled by the vehicle before any braking is applied. The second term ($V_0^2/2a$) is the distance required to bring the vehicle to a complete stop, assuming constant deceleration. These terms are illustrated in Figures 5-l and 5-2 respectively. The two values are added to determine the. total distance required.

For example, assume a travel speed of 70 ft/s (48 mph), a response time of 2 s and a deceleration of 0.55g's. From Figure 5.1, the distance traveled before braking is 140 ft and the distance to stop the vehicle is 138 ft. Thus the total distance required to bring the vehicle to a stop before. reaching the obstacle is 278 ft.

As can be observed from the graphs, there is a tremendous range in the distances required to stop. A fast-reacting (1.0 s), hard braking (0.7g) driver traveling at 44 ft/s (30 mph), requires 87 feet to bring the vehicle to a stop. However, a slower reacting (2.5 s) lighter braking (0.4 g) driver traveling at 88ft/s (60 mph) would require 521 feet, This suggests that quite long ranges are required to avoid the most demanding cases, while longer ranges increase the probability of false or nuisance alarms. System designers will have to analyze these tradeoffs to determine an optimal system.

Note that this model does not address the lead vehicle moving (and decelerating to a stop). case, which accounted for thirty-nine percent of this scenario in the clinical sample. However, the distance in Equation (1) is a conservative value, so that if this distance is available there cannot be a crash regardless of whether or not the lead vehicle is moving, decelerating or stationary. Clearly, a viable rear-end collision warning system would require a much more complex algorithm. This model is provided to bound the problem and illustrate the range of warning distances that would be required. For a more detailed assessment- of rear-end countermeasure concepts (addressing both lead-vehicle stopped and lead-vehicle moving situations), see (Knipling , et al , 1993)

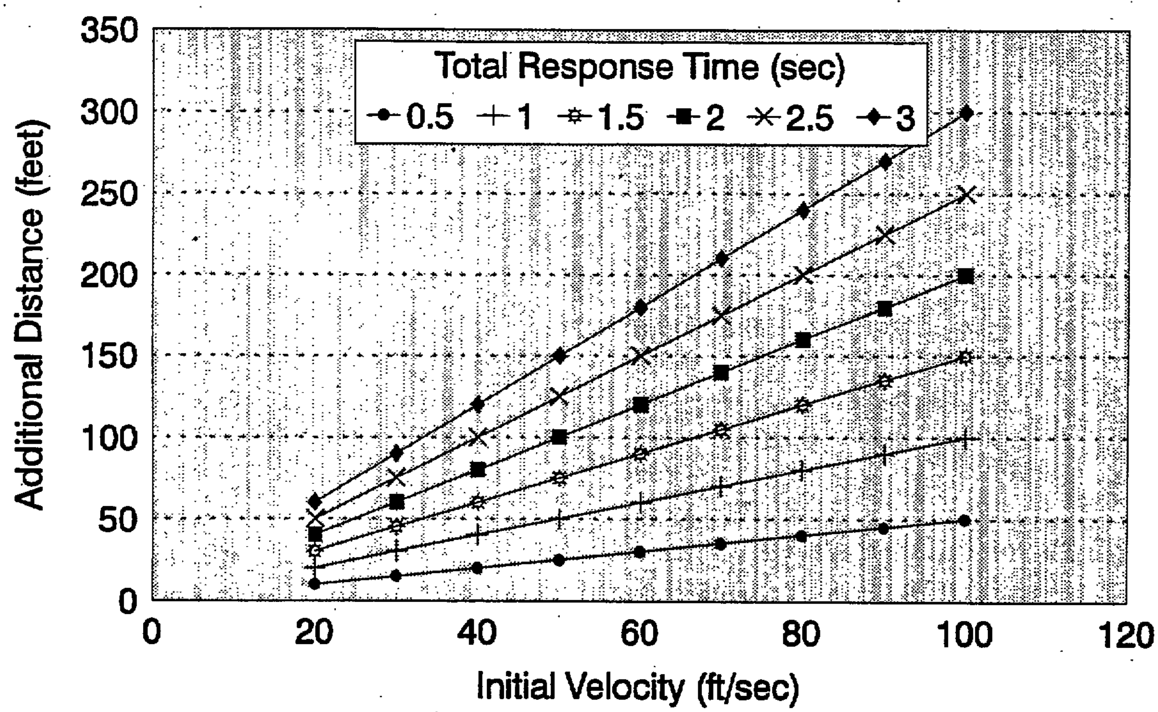


Figure 5-1. Distance Versus Velocity for Different Response Times

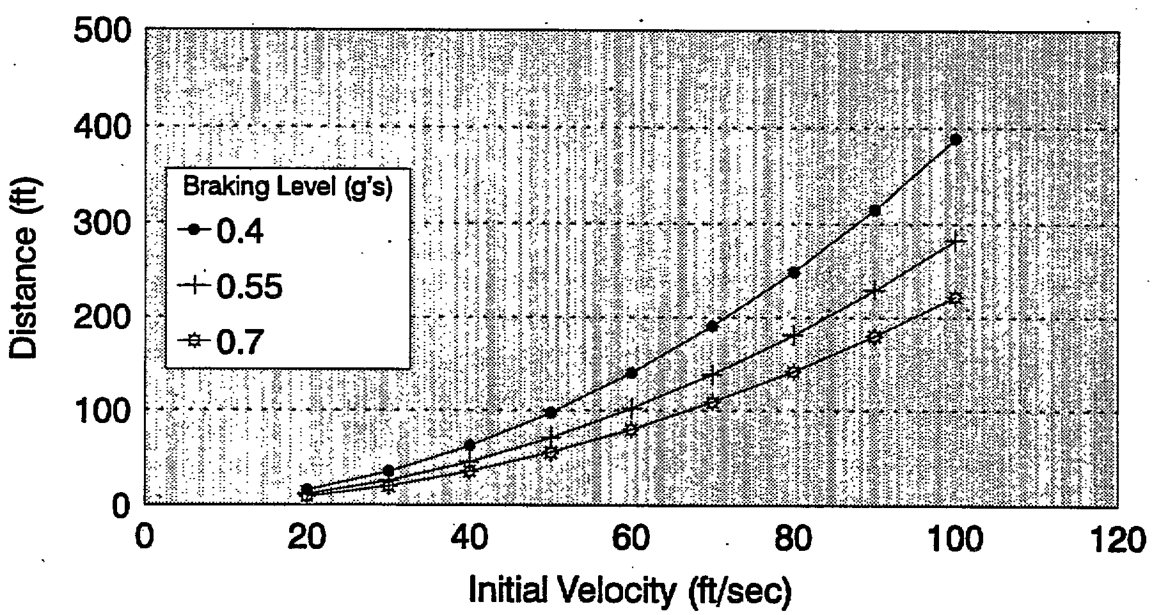


Figure 5-2. Stopping Distance Versus Travel Velocity for Different Braking Levels

5.3 LANE RETURN MODEL

<u>Straight road</u>

Many SVRD crashes involve gradual drifts off the roadway. The kinematic remedy would be to apply a lateral acceleration (through steering inputs) opposite to the direction of the drift. In the following model it is assumed that the vehicle is traveling at a constant velocity and a constant heading offset from the direction of the road (see Figure 5-3).

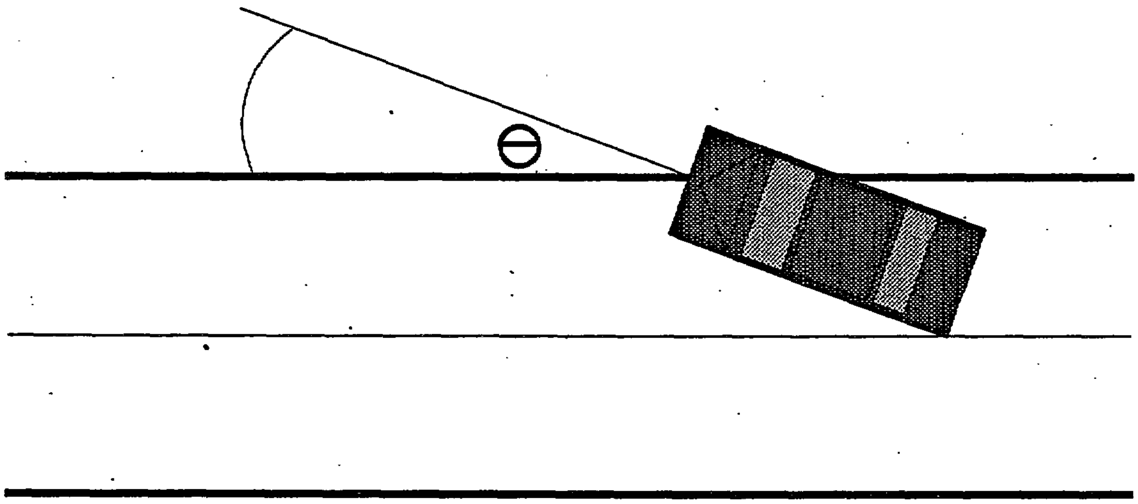


Figure 5-3. Schematic of Lane Departure

Once a detrimental heading is detected, the following lateral acceleration is applied either by the driver or with control intervention assistance:

$$a=\begin{cases} kt & \text{for } 0\le t\le t_{crit} \\ a_{\max} & \text{for } t>t_{crit} \end{cases} \tag{2}$$

where
- $a =$ lateral acceleration (negative for corrective action)
- $k =$ acceleration rate of change (negative)
- $a_{max} =$ the maximum value of acceleration (negative)
- $t_{crit} =$ the time required to reach a_{max}
  (t is assumed to be zero when the lateral acceleration is first applied)

The lateral velocity can then be derived from Equation 2 as:

$$V_{lat}=\begin{cases} V_0 \sin\theta+\frac{1}{2}kt^2 & for\ 0\le t\le t_{crit} \\ V_0\sin\theta+\frac{1}{2}kt_{crit}^2+a_{max}(t-t_{crit}) & for\ t>t_{crit} \end{cases} \qquad (3)$$

If the total lateral distance traveled by the vehicle when the lateral velocity reaches zero is greater than the lateral distance from the lane to the edge of the road, a SVRD crash is possible. This distance is the integral of Equation 3 and is given by:

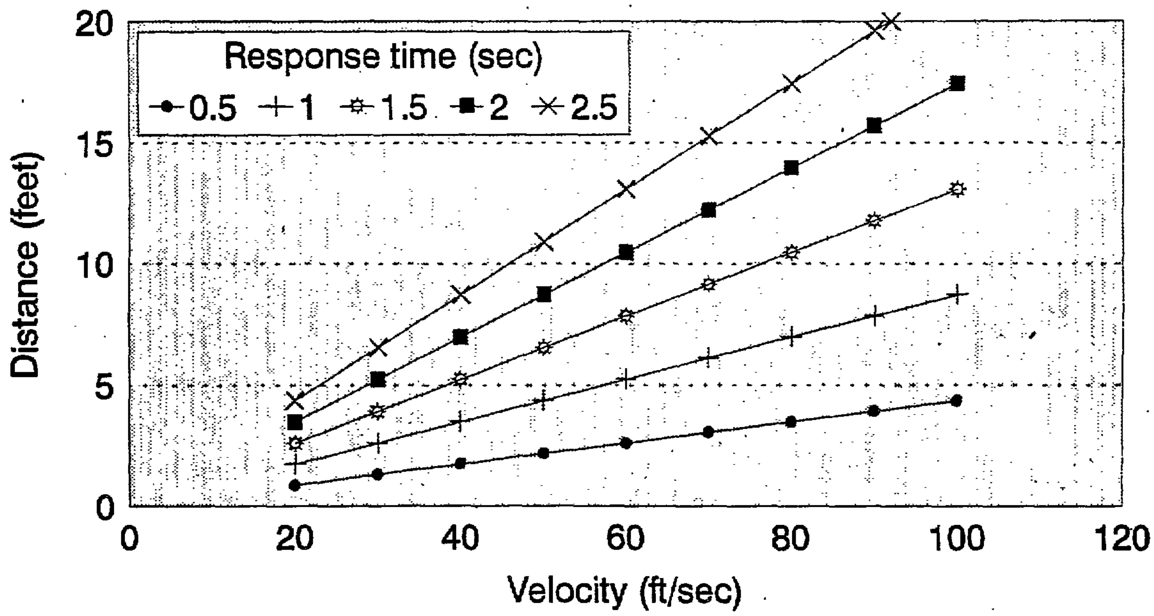
$$D_{lat}=\begin{cases} V_0 \sin\theta\ t_r+\ \frac{1}{6}kt^3+V_0\ \sin\theta\ t & for\ 0\le t\le t_{crit} \\ V_0\ \sin\theta\ t_r-\ \frac{1}{3}kt_{crit}^3\ +\ \frac{1}{2}kt_{crit}^2\ t\ +\ \frac{1}{2}a_{max}(t-t_{crit})^2+V_0\ \sin\theta\ t & for\ t>t_{crit} \end{cases} \qquad (4)$$

where
D_{lat} = lateral distance traveled
V_0 = initial velocity
θ = departure angle
k = acceleration rate of change
t_{crit} = time required to reach maximum acceleration
t_r = response time (between start of departure and application of corrective acceleration

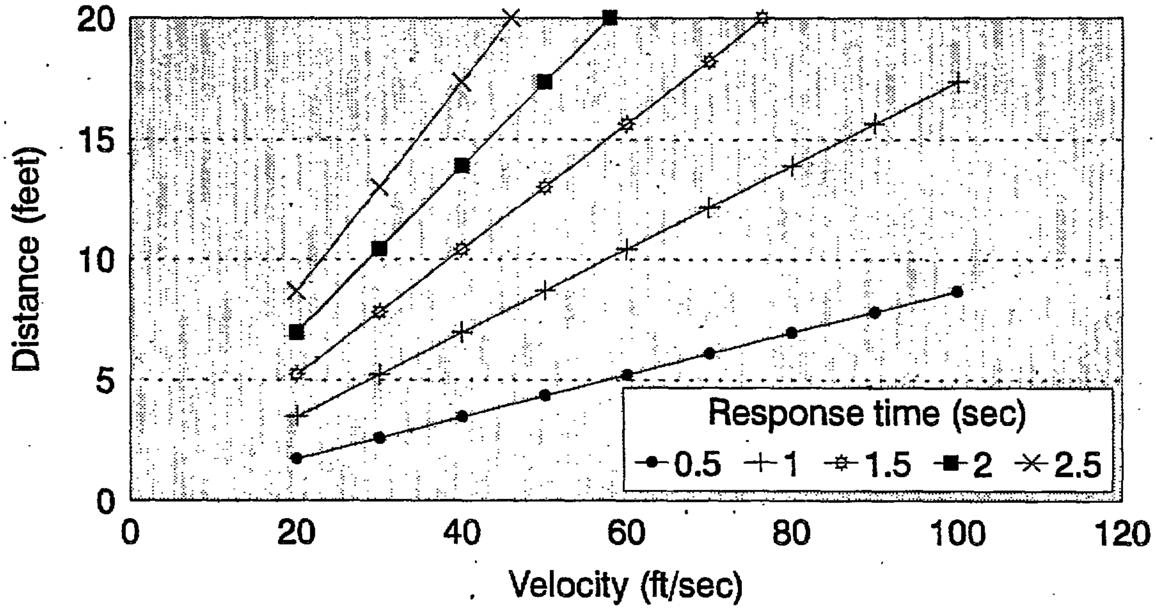
In order to determine the distance when the lateral velocity reaches zero, it is necessary to know the time when this occurs. The time is given by the following expression:

$$t=\begin{cases} \sqrt{\frac{-2V_0\ \sin\theta}{k}} & for\ 0\le t\le t_{crit} \\ \frac{-V_0\ \sin\theta}{a_{max}}+\frac{1}{2}t_{crit} & for\ t>t_{crit} \end{cases} \qquad (5)$$

This distance equation is illustrated in Figures 5-4a-d and 5-5a-l. Again the figures are separated into the distance travelled before any correction is applied, and the distance travelled completing the maneuver. Assume that a vehicle is traveling at 70 ft/s (48 mph),

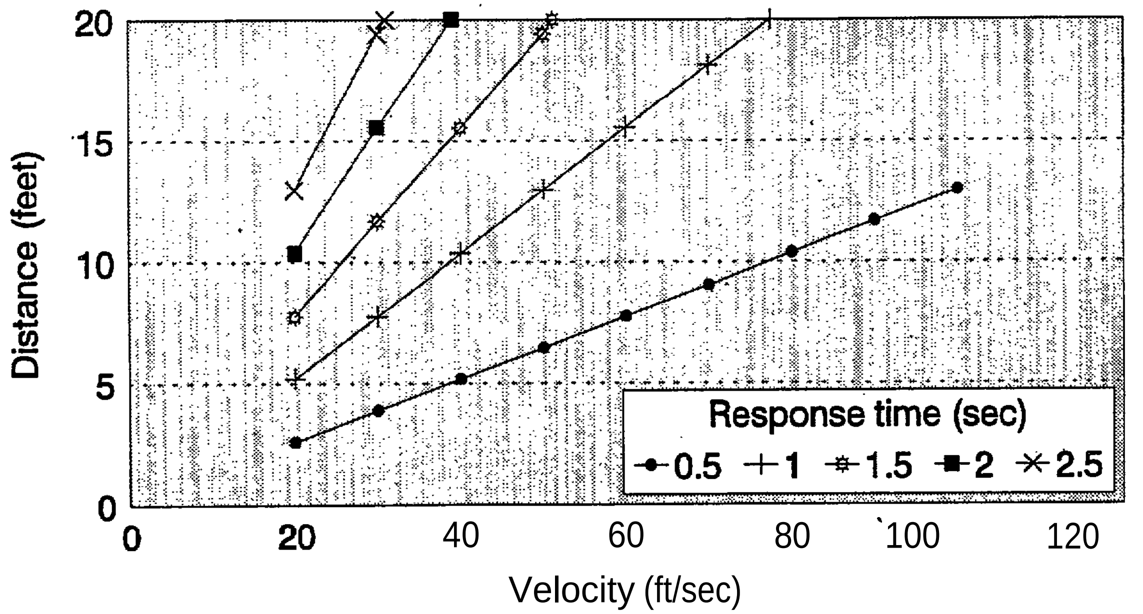


O = 5 deg
(a)



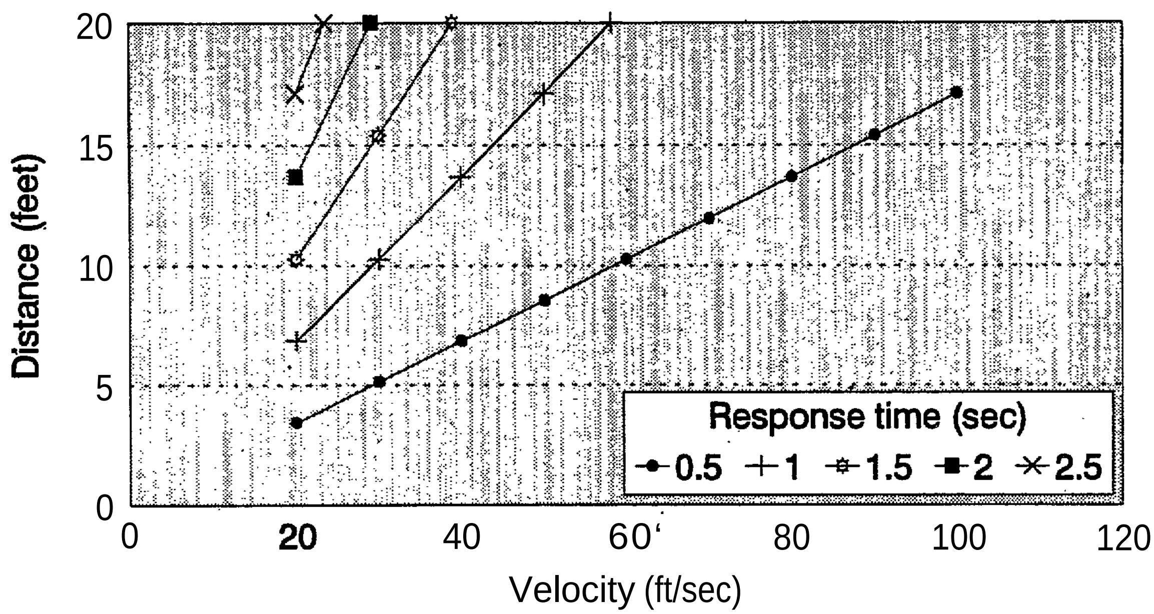
O = 10 deg
(b)

Figure 5-4(a-b). Lateral Distance Versus Velocity for Different Response Times and Departure Angles



O=15 deg

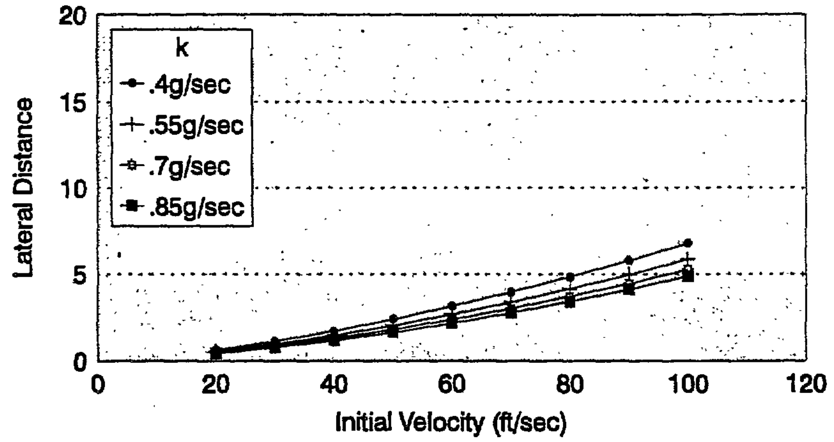
(c)



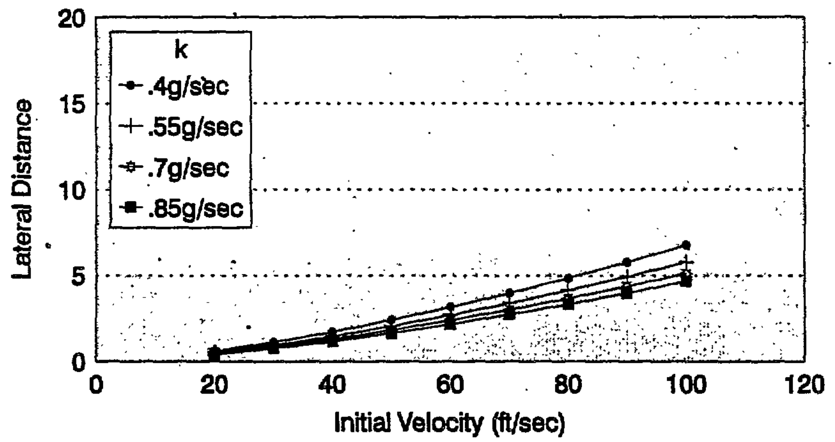
O=20 deg

(d)

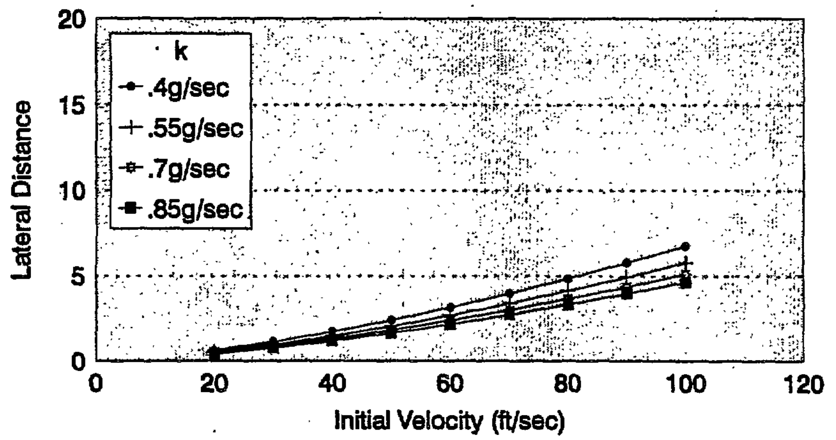
Figure 54(c-d). Lateral Distance Versus Velocity for Different Response Times and Departure Angles (cont.)



O = 5deg, amax=0.4g's
(a)

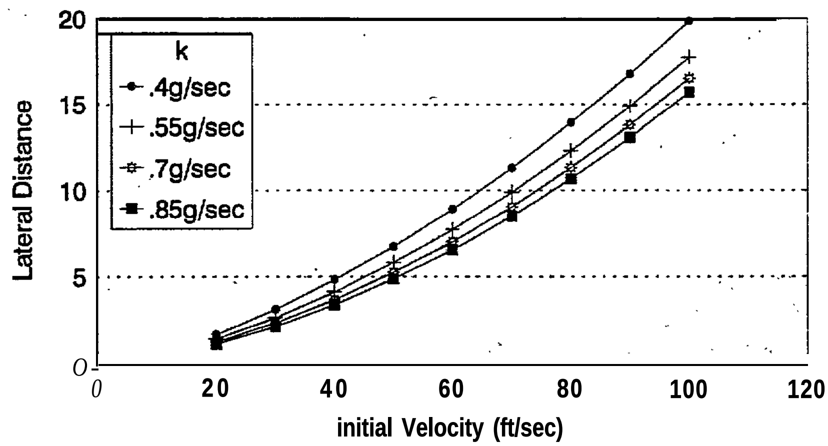


O = 5deg, amax=0.55g's
(b)



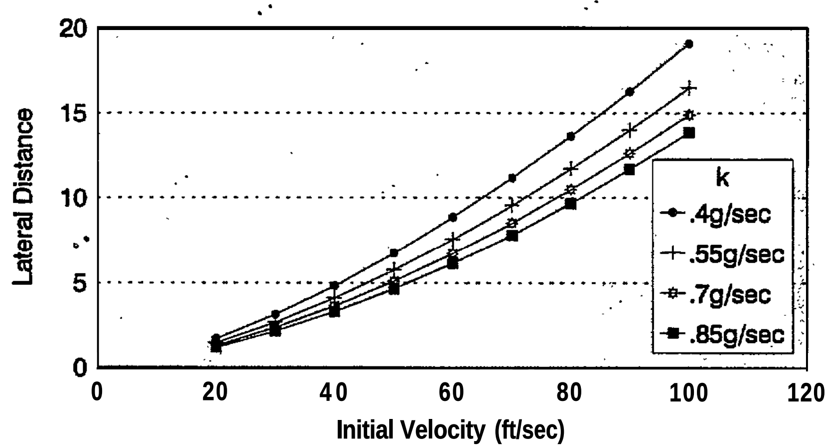
O = 5deg, amax=0.7g's
(c)

Figure 5-5 (a-c). Lateral Distance Versus Velocity for Different Departure Angles, Acceleration Rates, and Maximum Accelerations



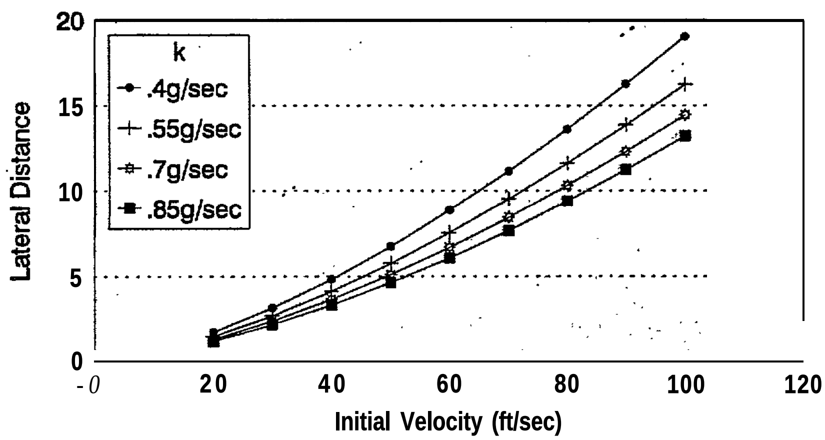
0 = 10 deg, amax = 0.4g's

(d)



0 = 10 deg, amax = 0.55g's

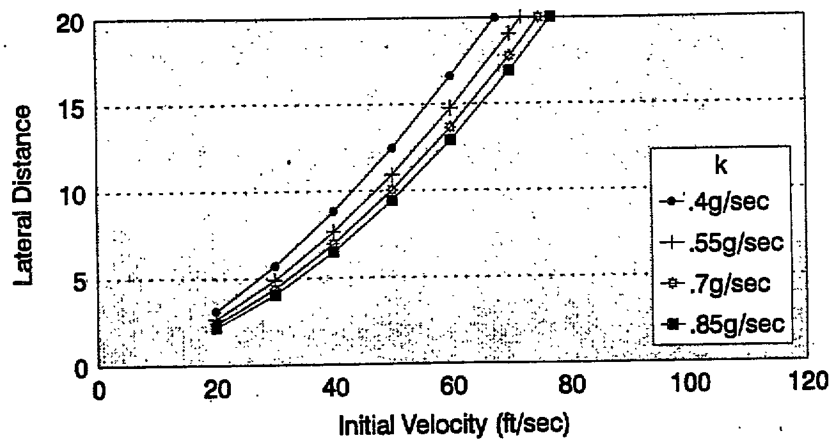
(e)



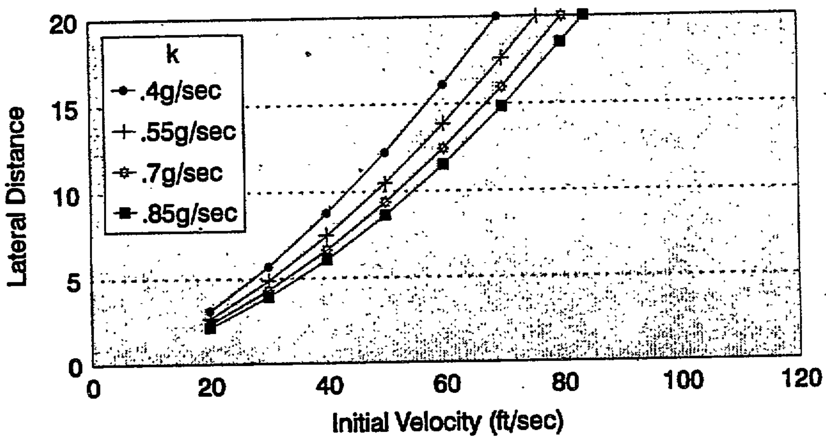
0 = 10 deg, amax = 0.7g's

(f)

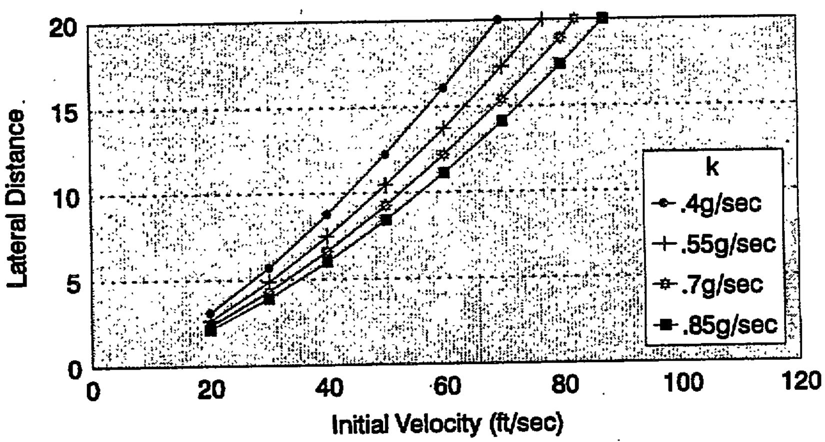
Figure 5-5 (d-f). Lateral Distance Versus. Velocity for Different Departure Angles, Acceleration Rates, and Maximum Accelerations (cont.)



O = 15deg, amax=0.4g's
(g)

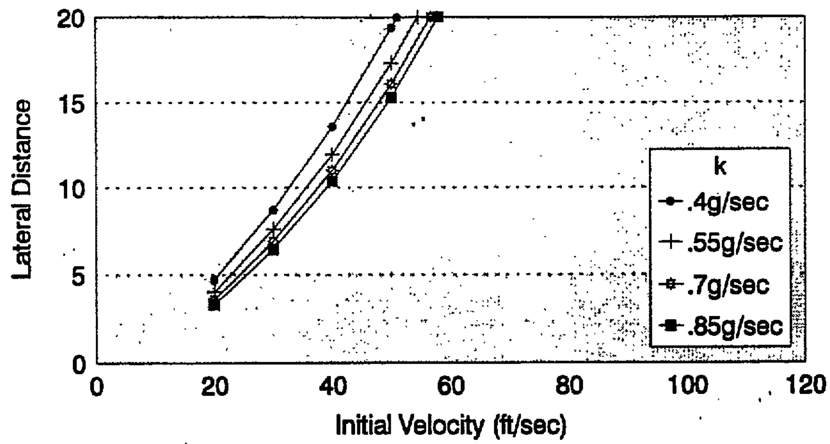


O = 15deg, amax=0.55g's
(h)

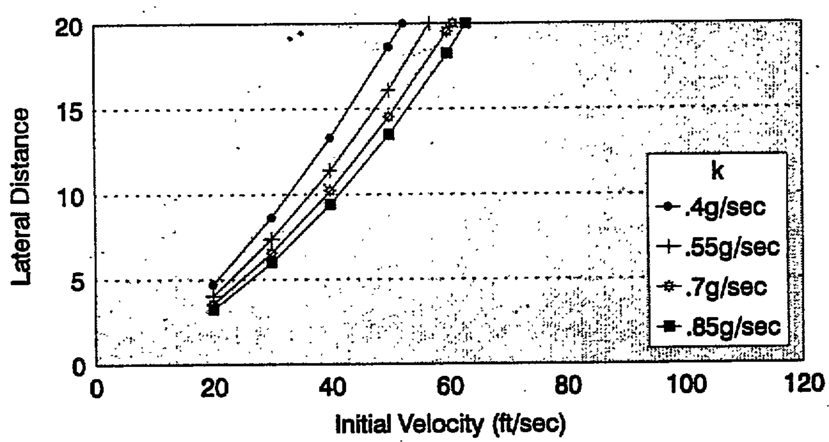


O = 15deg, amax=0.7g's
(i)

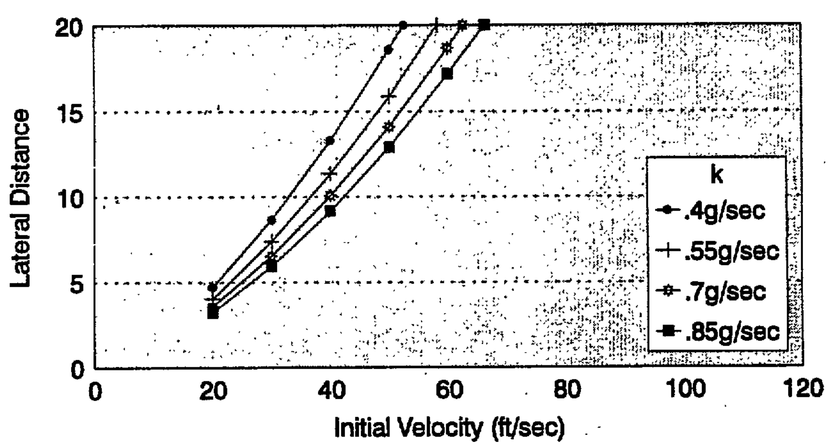
Figure 5-5 (g-i). Lateral Distance Versus Velocity for Different Departure Angles, Acceleration Rates, and Maximum Accelerations (cont.)



O = 20deg, amax=0.4g's
(j)



O = 20deg, amax=0.55g's
(k)



O = 20deg, amax=0.7g's
(l)

Figure 5-5 (k-l). Lateral Distance Versus Velocity for Different Departure Angles, Acceleration Rates, and Maximum Accelerations (cont.)

at a departure angle of 5 degrees, and that the response time will be 1 second. Further assume that the vehicle will respond with an acceleration rate of 0.7g's per second, reaching a maximum of 0.55g' s From Figure 5-4a, the vehicle will travel 6.1 feet before the acceleration is applied, and from Figure 5-5b, another 3.0 feet completing the maneuver, for a total of 9.1 feet..

As can be seen from Figure 5-5, the lateral distance required is not very sensitive to the maximum acceleration (a_{max}), since most of the movement occurs while the wheel is being turned, and the vehicle often has stopped its lateral movement before the peak acceleration is reached. The effect of the rate of change of acceleration (k) is significant, however it is greatly outweighed by the sensitivity to velocity, departure angle, and, from Figure 5-4, response time.

The detailed examination of eleven of the crash files examined in Chapter 3 indicated that typical departure angles ranged from 5 to 20 degrees. Also the distance between the edge of the lane and the first hazardous object ranged from 15 ft or more to as 'little as 1.5 ft. Clearly, a roadway departure will only result in a crash if there is a stationary object, embankment or other hazard in the vehicle's path. Yet since comprehensive knowledge of the entire terrain is not feasible, the only surely successful avoidance maneuver is one where the vehicle never departs the roadway. From the data presented above, however, the time and distance required seem greater than that which is available in all but the most favorable of cases.

Table 5-2 illustrates the maximum velocity at which the lane return maneuver can be successful. The assumed response time is 0.8 seconds based on studies to examine surprise steering reaction times (Malaterre, 1990). It does not include the time that would be required for an IVHS system to generate a warning. Also, the most optimistic value for maximum lateral acceleration (0.7g) and rate of change of acceleration (0.85g/sec) were chosen to set an upper bound.

For small lateral distances, 6 feet or less, a vehicle departing the road at 5 degrees must be travelling slower than 40 mph to be able to recover. At greater angles, the speeds become slower than one would expect to find in practice (20 mph or less).

At large departure angles (15 degrees or greater), crashes can only be prevented with long lateral distances, and even then only at slower speeds.

Many of the 5 degree departures could be prevented, particularly when 6 or more feet are available.

Note, however, that these data are for a fast reacting, fast steering, and high maximum acceleration driver. Slower drivers would have much less success safely returning to the travel lane. Also bear in mind that this model does not address the events after the lateral velocity is stopped. In some cases, the driver who has oversteered may lose control and depart the road on the opposite side or impact another vehicle. The stability of vehicles performing a severe steering maneuver must be examined.

Table 5-2. Maximum Velocity (mph) at which Lane Return is Possible (Upper bound)

Lat. Distance to Hazard (ft)	DEPARTURE ANGLE (Degrees)			
	5	10	15	20
2	14.9	7.5	5.0	3.8
4	27.4	13.8	9.3	7.0
6	39.1	19.6	13.2	10.0
8	50.1	25.2	16.7	12.8
10	60.6	30.4	20.3	15.4
12	70.6	35.5	23.7	17.9
14	80.2	40.3	27.0	20.4
16	89.6	44.9	30.1	22.8
18	98.6	49.4	32.9	25.0
20	107.4	53.9	35.8	27.3

Curved Road: The majority of SVRD crashes caused by gradual lane departure occurred on curved roads. Although it is possible for the curve to increase. the time available to react if the driver happens to drift into the curve, much more often the driver fails to track the curve and continues straight as the road turns underneath him. The initial angle of departure from the travel lane ranges from about two degrees for a road with a 2000 ft radius of curvature to seven degrees for a 200 ft radius. If the vehicle continues in its previous straight path the departure angle continues to increase during the response time. Then, the driver must not only return to zero lateral velocity as in the straight road case; but continue to steer so a's to follow the curve.

Due to the increased complexity of this situation, it is not within the scope of this report. However, the results from the straight road analysis indicate the great difficulty in avoiding this type of crash by initiating response once the vehicle has departed its lane.

For a more comprehensive analysis of lateral crash avoidance, see the lane change crash problem study (Chovan, et al., 1993).

5.4 SPEED REDUCTION MODEL

For some cases, the most effective method of reducing crashes due to poor traction or an approaching curve, for example, is to simply reduce the speed. This model determines the distance required for a vehicle to reduce its speed to a desired one. As in the previous models, this model is valid whether it is an aware driver slowing normally, a driver alerted by a countermeasure or an automatic system. Again, only the response times will be different. This distance is given by:

$$D_{SLOW}=V_0 t_R+\frac{1}{2a}(V_0^2-V_f^2) \tag{6}$$

where D_{SLOW} = Distance required
V_0 = Initial Velocity
V_f = Final (desired) Velocity
a = Deceleration
t_R = Response Time (between detection of hazard and application of brake)

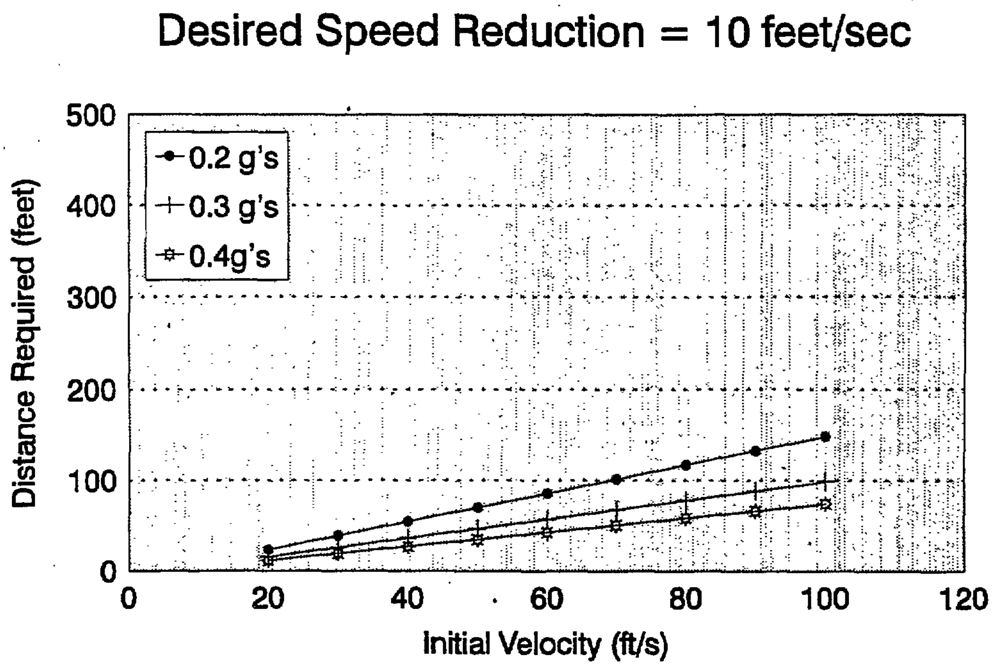
The first term is identical to that for the rear-end collision model, the distance traveled before braking is applied, and so the same Figure, 5-1 applies. The second term is the distance for the vehicle to decelerate to the desired speed and is illustrated in Figure 5-6. Again the values must be added to get the entire distance required to slow the vehicle.

Again consider a vehicle traveling at 70 ft/s(48 mph) with a response time of 2.5 seconds. Assume that because of wet roads, the speed should be reduced to 30 feet/seconds, and this will be done at 0.4g. So, the distance traveled before braking is 175 feet (from Figure 5-1) and the distance to reduce the speed is 155 feet (from Figure 5-6d) for a total of 330 feet. Since speed warnings need not be time sensitive, it should be possible to issue warnings far enough in advance so that all drivers are able to respond safely.

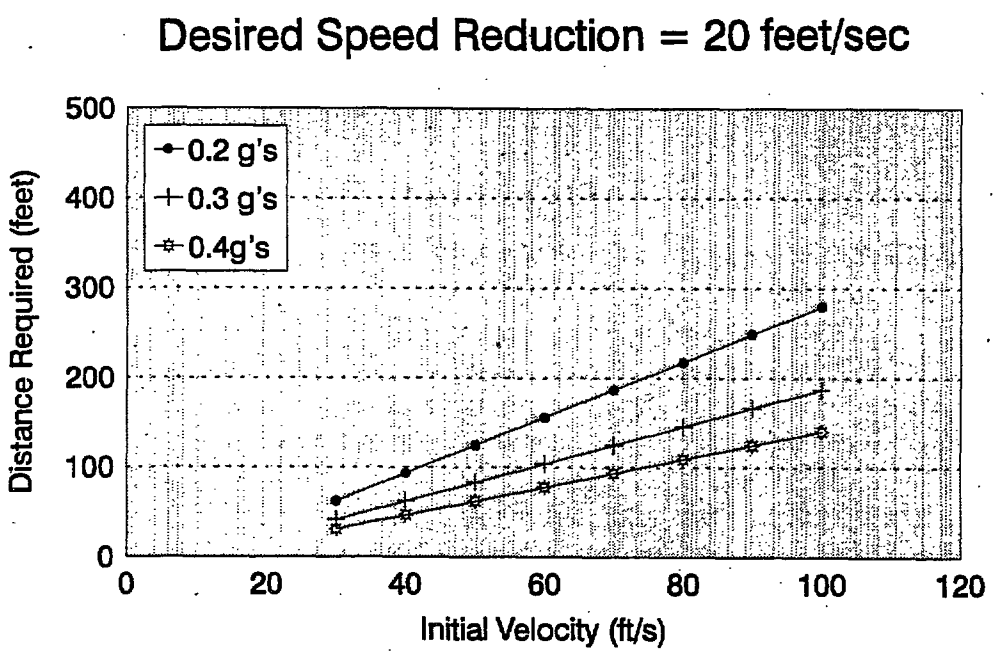
5.5 VEHICLE/OBSTACLE AVOIDANCE MANEUVER

This is largely the same control exerted by an attentive driver during normal driving. Normally, the driver assesses the situation, determines the velocities and likely paths of the other vehicle or object, determines where on the road he can safely maneuver, and applies the appropriate input to the steering wheel, brakes and/or accelerator.

Clearly, the exact nature of the maneuver is extremely sensitive to the details of the scenario, and there is no standard response to these sorts of maneuvers. It is conceivable that eventually an extremely sophisticated system might be developed that can measure and process this amount of information. However, its complexity is beyond the scope of this study, and this section is included for completeness.

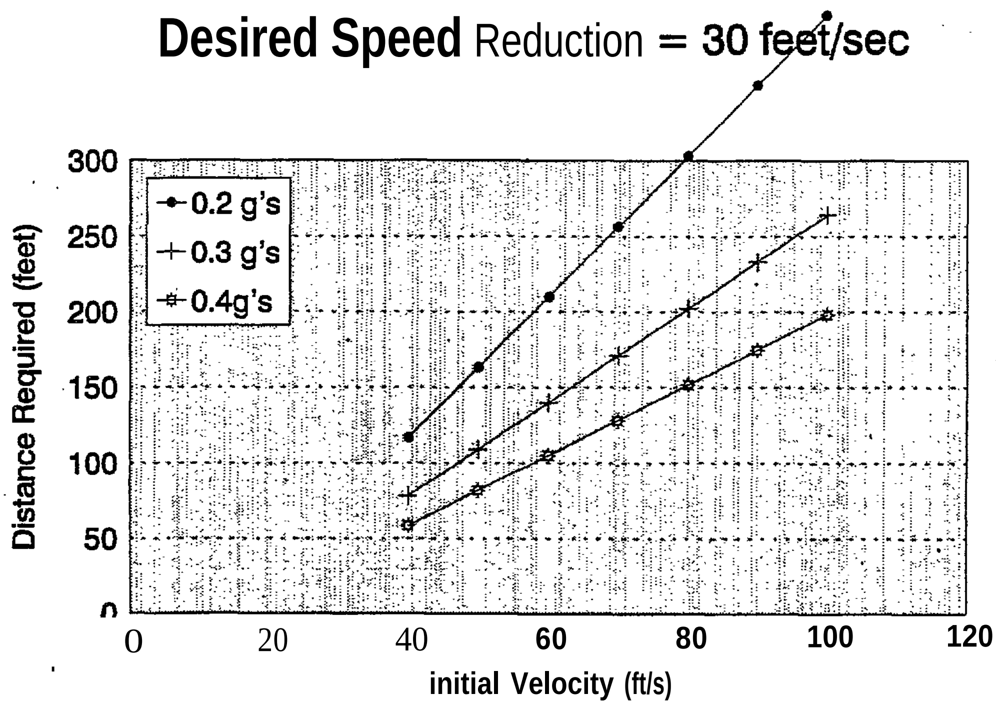


(a)

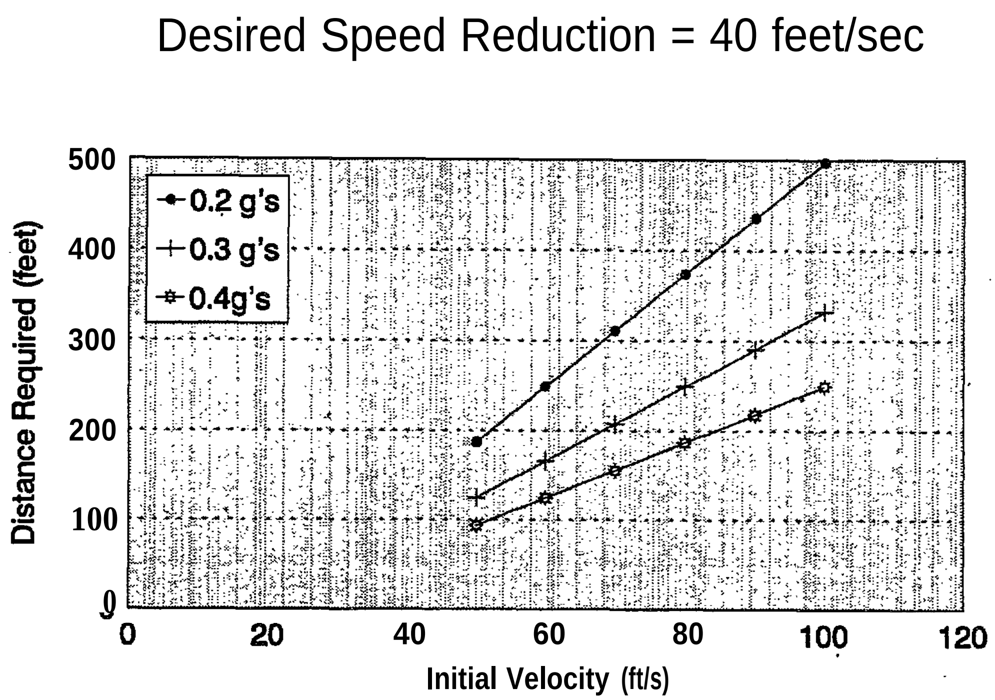


(b)

Figure 5-6 (a-b). Distance Required to Slow Vehicle Versus Desired Change in Velocity for Different Braking Levels



(c)



(d)

Figure 5-6 (c-d). Distance Required to Slow Vehicle Versus Desired Change in Velocity for Different Braking Levels (cont.)

6. RESEARCH NEEDS

To estimate the effectiveness of a countermeasure two types of data are required the data to define the crash scenario (e.g., statistics on roadway geometry, vehicle speed and acceleration, and driver reaction times) and information on the proposed countermeasure (algorithm, range, accuracy, etc.). This second essential group will not be examined here but will be addressed by other NHTSA efforts. Instead this chapter will focus on what data are needed to achieve a better understanding of the crash problem.

6.1 PROBLEM SIZE AREA

- Problem size estimation for crashes is typically based on only one year's data. It would be beneficial to conduct a trend analysis across successive years. to determine how the particular crash problem is evolving. For example, decreased alcohol use and demographic shifts in drivers will affect crash characteristics.

- There are certainly a large number of roadway departures where no injuries or even property damage occurs, many of which are never reported to the police and therefore never appear in the crash statistics. Yet these could have been severe had there been a roadside object such as a tree, rock or utility pole. More accurate measures of the size and circumstances of these events would help further define the problem.

6.2 CLINICAL ANALYSIS AREA

- Relatively few cases were studied for crash subtype and causal factor analysis. There were also many causal factors cited without one dominant cause. Further examination would lead to a better categorization of these crashes, and could lead to the identification of other significant types.

- Since clinical analysis is a subjective process, it would be beneficial to compare the results of two analysts working on the same data set. This would help determine the extent to which the causal factor results can be replicated.

- A set of "pre-crash variables" was added to the GES and CDS since this analysis. These will codify any accident avoidance maneuvers undertaken by the drivers prior to crashing. Further analysis of this data can provide addition insight into opportunities for countermeasures.

6.3 REAR-END CRASH SUBTYPE

- To understand this subtype we need a better understanding of the kinematic variables such as velocities of both vehicles, the response time distributions, the distance between vehicles when braking is initiated, and the braking levels of each vehicle. It is also important to determine the drivers response to a warning system, and the gaps at which warning is acceptable. (See Knipling, et al., 1993)

6.4 LANE RETURN SUBTYPE

- More thorough data can be obtained from the accident files regarding the departure angles and the travel speed of the vehicles. A more comprehensive study of SVRD crashes is needed to more accurately bound the problem.

- Additional information on the width of the shoulders by roadway type is needed to determine the time intervals available for action.

- Additional driver information is also needed on steering response times, rate of change of lateral acceleration and maximum lateral accelerations reached when attempting to avoid accidents.

- Drivers leave their lane with some regularity during normal driving (e.g., passing a pedestrian or bicyclist, avoiding potholes, yielding right of way to an emergency vehicle). It is necessary to determine the'frequency and magnitude of such intentional, departures in order to distinguish true alarms from nuisance alarms.-

6.5 SPEED REDUCTION SUBTYPE

- To determine the effectiveness of these countermeasures, information on several issues is required. These include the typical distribution of travel speeds versus posted speeds, driver response to speed advisories, in terms of both compliance and deceleration levels.

6.6 INTOXICATED DRIVERS

- Intoxicated drivers contribute significantly to the SVRD crash problem. Some countermeasures have been proposed to address this issue directly. While most countermeasures discussed here will be of some use for the case of intoxicated drivers, it would be useful to determine rates of compliance to countermeasure warnings, and driver attributes for these cases.

6.7 VEHICLE MOTION ENVIRONMENT

- Police accident reports and similar crash data generally provide little data on precise vehicle locations and motions. And, of course, they provide no data on non-crash-related vehicle motions. Such data would greatly strengthen the basis for countermeasure modeling since it would provide empirical data on driver behavior and vehicle motion. An archival knowledge base of vehicle location and motion would provide empirical data relating to such SVRD crash-related issues as vehicle trajectories around turns, inter-vehicle gaps, deceleration rates, and loss-of-control episodes. Data on “normal driving” and “near miss” situations could be used’ to model crash situations. For example, the degree to which vehicle speeds and trajectories while approaching turns are predictive of how (and how well) the vehicle negotiates the curve could be determined. NHTSA has addressed this research need by initiating a program to develop a specialized measurement system to quantify the “vehicle motion environment” (Ervin et al., 1993). At a given road site, the program will use roadside imaging devices to capture passing vehicle motion variables and provide discrete data and statistical distributions of these variables. Vehicle trajectory data obtainable by such a system would enable significant refinements to the current modeling.

6.8 ADDITIONAL QUALITATIVE DATA

- For the evasive maneuver related crashes, the circumstances of the crash must-be known in greater detail. Specifically, what other options were available to the driver and how could an IVHS system have prevented the crash.

- For the opposite direction encroachment cases, what caused the principal other vehicle to leave its travel lane. Perhaps the most effective countermeasure would ‘act on this vehicle rather than the subject vehicle.

- Why were the drivers in the, excessive speed cases traveling so quickly? The answer to this will determine whether the solution to-the problem is information or enforcement based.

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APPENDIX

Case Weighting Scheme

Crash Severity	# in Sample	% of Sample	% of 1990 GES	Case Weight	% Rep. by Each Case
0 (O)	48	48%	65.8%	1.37	1.37%
1 (C)	14	14%	11.0%	0.79	0.79%
2 (B)	17	17%	14.4%	0.85	0.85%
3/4 (A/K)	21	21%	8.7%	0.41	0.41%
Total	100	100%	99.9%	99.88	99.88%

Notes

1) GES crash severity based on cases involving passenger vehicles. Cases of unknown severity (7.7% of the GES sample) were counted as "O" cases.

2) There is an implicit assumption that, within each severity level, the sample cases are representative of the national crash experience (e.g., GES). In other words, there are no biases in the CDS case selection or, within CDS, in the selection of the reconstruction sample.

3) Severity levels 3 and 4 (A and K) are combined because of the small number of cases (4 K).

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