COMPARATIVE ASSESSMENT OF CRASH CAUSAL FACTORS AND IVHS COUNTERMEASURES

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ABSTRACT

The National Highway Traffic Safety Administration's Office of Crash Avoidance Research, in conjunction with the Research and Special Programs Administration's Volpe National Transportation Systems Center, has underway a multi-disciplinary program to: identify crash causal factors and applicable Intelligent Vehicle-Highway System countermeasure concepts, model crash scenarios and avoidance maneuvers, provide preliminary estimates of countermeasure effectiveness when appropriate, and identify research and data needs. To date, five crash types have been examined which include rear-end, backing, single vehicle roadway departure, lane change, and intersection/crossing path crashes. This paper describes the methodology employed in analyzing crash scenarios and developing functional countermeasure concepts independent of specific technologies. To illustrate that methodology, several steps in the lane change crash analysis are presented. In addition, the causal factors of four subtypes of intersection/crossing path crash problems are tabulated and functional countermeasure concepts are devised based on a matrix of crash causes and subtypes. Finally, the causal factors of the five crash types mentioned above are synthesized in separate categories dealing with the driving task, driver physiological state, and the driving environment.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) has undertaken major research programs to facilitate and stimulate industry efforts which result in the deployment and commercialization of cost- and safety-effective Intelligent Vehicle-Highway System (IVHS) products (1). One major thrust in NHTSA's program is defining crash avoidance opportunities to aid the development and implementation of IVHS technologies for improving the crash avoidance capabilities of the driver-vehicle system. A key element of that thrust is the problem definition and analysis of target crashes and IVHS/countermeasure actions. The preliminary stage of this work is being performed by the Research and Special Programs Administration's (RSPA) Volpe National Transportation Systems Center (VNTSC) in conjunction with NHTSA's Office of Crash Avoidance Research- (OCAR), with contract support from Battelle Memorial Institute and its subcontractor ARVIN/Calspan. This project has developed and applied a methodology for analyzing target crashes and IVHS/crash countermeasure actions for the purpose of assessing potential effectiveness and identifying research and data needs.

Initially, seven major crash types are being addressed in this project:

- Rear-End
- Backing
- Lane Change
- Single Vehicle Roadway Departure (SVRD)
- Intersection/Crossing Path (I/CP)
- Reduced Visibility (Night/Inclement Weather)
- Head-On

Figure 1 shows the number of Police-Reported (PR) crashes (1991 General Estimates System (GES)) for six target crash types which are all mutually exclusive (2). The reduced visibility crash size is not shown in Figure 1 because this is a crash ***circumstance,*** not a crash type, and overlaps with the other crash types shown. According to 1991 GES statistics, approximately 43% of all crashes occurred in non-daylight (dark, dark but lighted, dawn, or dusk) or in bad weather (rain, sleet, snow, fog, or smog) conditions. Other crashes that account for 31.1% of all crashes involve pedestrians/cyclists, on-road rollovers, other intersection crash types, non-lane change sideswipes, non-intersection crossing paths, etc. The relative crash sizes in Figure 1 are used as weighting coefficients, later in this paper, to determine the weighted average of causal factors of rear-end, backing, lane change, SVRD, and I/CP crashes.

To date, individual reports on rear-end (3), backing (4), and lane change (5) crashes have been published and are available from the National Technical Information Service (NTIS). Individual reports on SVRD, reduced visibility, and head-on collisions are in preparation and will be published as they become available. As for the I/CP crashes, three separate reports are in preparation which address the following subtypes: Signalized Intersection/Straight Crossing Path (SI/SCP), Unsignalized Intersection/Straight Crossing Path (UI/SCP), and Intersection/Left-Turn Across Path (I/LTAP).

These crash problem analyses include a detailed review of individual cases, identification of relevant pm-crash circumstances, and preliminary assessment of some mechanisms of intervention. These analyses contribute to the development of performance specifications for IVHS crash avoidance systems by identifying preliminary functional requirements of countermeasure concepts. Other programs, such as NHTSA's program to develop performance specifications for advanced collision avoidance systems (6) (7), will build on these analyses.

This paper is divided into three parts. The first part reviews the analytical methodology being followed in these analyses. To illustrate the first five steps of this methodology, the results of the lane change crash analysis are presented The second part provides a preliminary assessment of causal factors and countermeasure concepts for I/CP collisions. Finally, the third part summarizes the causal factors of target crashes analyzed to date.

METHODOLOGY FOR CRASH PROBLEM -ANALYSIS

The methodology employed in crash analysis, shown in Figure 2, has emphasized the analysis of target crash scenarios and applicable avoidance maneuvers and the development of functional countermeasure concepts. The rear-end (3) and backing (4) crash problems have been analyzed based on this methodology which was described previously in (1). The effectiveness of countermeasures was predicted by means of countermeasure intervention models and available data on countermeasure technology, driver behavior, and vehicle performance. Assumptions were made to substitute for unavailable data which dealt with warning logic criteria and probability distribution function of driver reaction time to warning signals. Specific elements of this methodology include the following:

- Baseline crash problem sizes are quantified and crash characteristics are described from General Estimates System (GES) and Fatal Accident Reporting System (FARS) crash databases.
- Contributing circumstances for each crash subtype are identified by an assessment of individual crash investigation case files.
- IVHS countermeasure concepts, whose functional requirements depend largely on the crash scenario itself, are devised based on crash subtypes and causal factors.
- First-level kinematic models are derived which describe the crash subtypes and possible evasive actions of the driver-vehicle system needed to avoid the crash (i.e., braking or steering). These models provide a means for analyzing the time available to take evasive action and the intensity of action needed to avoid the crash, as illustrated in Figure 3 (7).
- Sensitivity curves are developed based on above kinematic equations which show either the time or distance available for the driver-vehicle-countermeasure system to avoid the crash in terms of other crash avoidance parameters.
- Parameters of the kinematic models are matched with the functional requirements of each applicable countermeasure concept in order to derive effectiveness estimates. Current data

are then assessed in terms of availability and suitability so as to determine whether reliable countermeasure effectiveness estimates **can** be computed.

- Finally, research and data needs are identified which may enhance the analysis of baseline target crash problem, countermeasure interventions, and human factors, and guide the development of proposed countermeasure concepts.

Effectiveness estimates have not been derived in lane change, I/CP, and SVRD crash analyses due to a lack of situation-specific data on driver and vehicle crash avoidance system capabilities. Instead, the analysis has concluded with modeling of basic relationships among key pre-crash parameters such as separation distance, closing speed, and driver ***response*** capabilities. To illustrate the methodology described above, the results of the lane change crash analysis (5) are summarized next.

ANALYSIS OF LANE CHANGE CRASHES

The “lane change” refers to a family of maneuvers that includes simple lane change, merge, exit, pass, and weave maneuvers. ***A*** lane change crash ***occurs*** when a driver of ***the Subject Vehicle*** (SV) attempts to change lanes and sties or is struck by another vehicle in the adjacent lane, referred to ***as the Principal Other Vehicle (POV) . The*** selected cases involve two vehicles. Thus, single vehicle crashes that were coded as lane change maneuvers were excluded from the analysis. GES statistics, based on a nationally-representative sample of Police Accident Reports (PARs), indicate that in 1991 approximately 244,000 crashes - 4% of the total - were lane change/merge crashes. Lane change crashes also accounted for 0.5% of the fatalities (225) in the data base. Additionally, approximately 386,000 non-police reported lane change crashes occurred (8). The 1991 GES statistics indicate that about 68% of lane change crashes were simple lane change maneuvers, as opposed to merge, exit, or weave maneuvers, and that passenger cars are about equally likely to be involved in left-to-right and right-to-left lane change maneuver crashes.

Crash Subtypes and Causal Factors

The analysis of lane change crashes was based on 16 hard copy reports and 144 PARS which were selected from the 1992 Crashworthiness Data System (CDS) and from the 1991 GES within the National Accident Sampling System (NASS), respectively. The cases used in the analysis were weighted for severity so that they might more closely approximate the national profile. The percentage breakdown of principal causes of lane change crashes is as follows:

- Did not see POV: 61.2%
- Misjudged gap/velocity: 29.9%
- Drift/Inattention: **3.8%**
- Evasive maneuver: **2.6%**
- Vehicle speed + bad surface condition: **2.2%**
- Tire blowout: **0.3%**

Two subtypes of the lane change crash were identified in the GES data set: proximity and fast approach. These are illustrated in Figure 4 for different vehicle relative positions along with their crash distribution. In the proximity case, there is little or no longitudinal gap and the velocity differential between the SV and the POV is minimal. In the fast approach case, there is a significant longitudinal gap between the SV and POV prior to the start of the lane change maneuver, and this gap is being closed at a substantial velocity differential between the two vehicles.

Crash Countermeasure Concepts

IVHS crash countermeasure concepts are devised based on the time-intensity graph of Figure 3.

The first applicable countermeasure is to prevent the start of the hazardous maneuver by the use of a ***presence indicator.*** For proximity crash avoidance, such system might continuously sense other vehicles and provide an information display (visual, auditory, other) when a vehicle is present in an adjacent lane. Detection coverage over the full length of the SV, on both sides, is needed since many proximity crashes involve vehicles outside the SV blind zone (i.e., side-by-side and rearward overlap cases). A design challenge of a presence indicator is to inform drivers of critical information at critical times in order to prevent the system from becoming a nuisance or an in-vehicle distraction source. .A plausible concept would activate the IVHS system only when turn signals are used. One problem with this concept is that drivers do not always use their turn signals.

The second applicable countermeasure is a ***driver warning*** system. This would only be activated if a collision were imminent but with enough time that driver intervention alone is feasible for crash avoidance. Vehicle performance and IVHS system lags consume some of the available time to respond. In addition, a warning system implies some threshold condition for alarm. This might be lane change start, signaled by some means, and detection of other vehicles that pose hazards. ***Control-intervention*** systems are the third type of countermeasure concepts. This is an alternative (or possibly a supplement) to a collision warning system and would be activated beyond the point where driver warning alone is likely to be effective. For instance, variable resistance steering in the SV and soft braking in the POV might be applied to avoid proximity and fast approach forward lane change crashes, respectively. In the event of a false alarm, the driver should be able to easily disengage the partial automatic controls. Finally, *fully* ***automatic control*** systems are applicable if the time available to avoid a crash dictates that driver time delays must be near zero.

Modeling Representation

To illustrate the fourth step of the methodology, the proximity subtype of lane change crash is kinematically modeled, assuming both the SV and POV initially travel at constant longitudinal velocity. The reported data do not readily provide a basis for more definitive statements on relative velocity. As a first approximation, the *normal lane change maneuver* can be modeled as a sine function of time for lateral acceleration. Consequently, the lateral distance d traveled during a lane change is expressed as:

$$d = \left(\frac{ILCD}{t_{LC}}\right)t - \left(\frac{ILCD}{2\pi}\right)\sin\left(\frac{2\pi}{t_{LC}}t\right) + v_0 t + d_0 \qquad (1)$$

where, $ILCD \equiv$ intended lane change distance (ft)

$t_{LC} \equiv$ total time to complete the lane change (s)

$v_0 \equiv$ initial lateral velocity (ft/s) (assumed 0 at lane change start)

$d_0 \equiv$ initial lateral distance (ft) (assumed 0 at lane change start)

The expression for the lateral velocity is easily derived from Equation (1) by differentiation. An IVHS system-initiated crash avoidance steering maneuver in the SV ends the sine model of normal lane change with a step input in steering away from the POV. Thus, the *crash avoidance steering maneuver* may be described by a trapezoidal acceleration model with a maximum recovery acceleration value that the driver does not exceed, as follows:

$$a = \begin{cases} a_0 - kt, & a < A_r \\ A_r, & \text{otherwise} \end{cases} \qquad (2)$$

where, $a_0 \equiv$ lateral acceleration at the start of recovery maneuver (ft/s^2)

$k \equiv$ rate of change in recovery acceleration buildup (ft/s^3)

$A_r \equiv$ peak recovery acceleration (ft/s^2)

By successive integrations, the lateral velocity and distance are derived. It is noteworthy that the lag between steering input and lateral acceleration is represented in the rate of change parameter, k.

The above modeling representation allows for estimation of crash avoidance requirements for the proximity lane change crash subtype (i.e., the time and distance available for crash avoidance by means of SV steering evasive maneuvers). The modeling parameters are summarized in Table 1 that lists, in addition to parameters delineated earlier, the lateral gap (LATGAP) between the SV and POV at the start of the lane change. As an example for crash avoidance requirements, a plot is shown in Figure 5 which indicates the maximum available time ($t_{available}$) in seconds to enable the SV to avoid a collision with the POV by means of an evasive steering maneuver. The graph shows $t_{available}$ for every combination of ILCD between 9 ft and 15 ft, in 1 ft intervals, and t_{LC}, ranging between 2 s and 16 s in 1 s intervals. The value of $t_{available}$ is determined iteratively under the two conditions: (1) lateral velocity= 0 and (2) total lateral distance traveled < LATGAP. Note that the available time must accommodate both IVHS system delays and driver steering reaction times. For a fixed IVHS system delay, $t_{available}$ can be used to estimate the proportion of drivers **who** might be able to respond within that time based on a distribution of surprise steering reaction times. In addition, $t_{available}$ can determine whether partial or fully automatic control-intervention systems may be requited for successful evasive maneuvers. Finally, negative values of $t_{available}$ indicate the case when a crash could not be avoided under any circumstances.

ANALYSIS OF INTERSECTION/CROSSING PATH CRASHES

This target crash problem deals with intersection SCP and LTAP crash configurations for both signalized (e.g., three-phase light signals) and unsignalized (e.g., stop signs) intersections. In the

SCP crash, two vehicles collide at right angles when both are attempting to pass through an intersection. In this situation, the SV crosses the intersection by running either a red light or a stop sign while the POV has the right-of-way. In the LTAP crash, two vehicles collide at an angle when the SV is attempting to turn left across the path of the POV. 1991 GES-based statistics have shown that SCP crashes at signalized intersections were 251,596 or 4.1% of all PR crashes and 484,470 at unsignalized intersections or 8.0% of all PR crashes. In addition, LTAP crashes amounted to 204,084 or 3.3% and 123,641 or 2.0% of all PR crashes at signalized and unsignalized intersections, respectively. This crash problem is addressed by the project team in three separate reports dealiig individually with UI/SCP, SI/SCP, and I/LTAP crashes.

Crash Subtypes and Causal Factors

The results of the causal factor analysis of the four subtypes of intersection crashes are summarized in Table 2, which are based on 295 cases and weighted to be nationally representative. Driver inattention to either stop sign or signal presence and light status appears more dominant in both SCP crashes than in the LTAP's, while vision obstructed by intervening vehicles is more dominant in both LTAP crashes than in SCP's. In contrast, deliberate violation of signal/sign is almost evenly distributed between both SCP and LTAP crashes. Moreover, only the UI/SCP crash subtype includes cases where the subject vehicles did actually brake but did not have an adequate stopping distance due to wet/icy pavement.

The analysis of the UI/SCP crash subtype revealed two major sub-subtypes: ran stop sign and stopped and proceeded against cross traffic which accounted for 42.4% and 57.6% of all UI/SCP crashes, respectively. The latter crash sub-subtype involves **SV drivers** who initially stopped as required and then attempted to cross the intersection without yielding to cross traffic. Driver errors in the "ran stop sign" scenario include driver inattention, vision obstructed, violation of sign, and driving under the influence. On the other hand, “proceeded against cross traffic” scenario is primarily caused by looked-did not see, misjudged gap/velocity, and vision obstructed. SV drivers committed all the signal/sign violations in both SCP crashes while, in contrast, POV drivers were cited for such violations in 19.9% of the SI/LTAP crashes compared to only 7.6% for SV drivers. In addition, improper signalling by the POV was observed in both LTAP crashes, where the driver signalled a turn but proceeded to go straight and hit a turning SV.

Crash Countermeasure Concepts

IVHS crash countermeasures for I/CP are devised with various functional requirements based on the matrix of crash causes and subtypes listed in Table 2. Moreover, these countermeasure concepts are layered at different levels of operational complexity that increase with the tune-intensity curve of pre-crash avoidance requirements in Figure 3. Most crashes caused by errors in the driving task are amenable to countermeasures that depend on the specific crash scenario and relative dynamics. In addition, the applicable first-level IVHS countermeasures vary with these error types. For instance, a recognition error may be remedied by a simple proximity traffic situation display while an action error may be mitigated by either a partial or fully automatic control intervention. Driver warning and control-intervention systems are also applicable to crashes caused by recognition errors as second- and third-level countermeasures, respectively. On the other hand, applicable first-level countermeasures which are independent of any crash scenario alleviate crashes caused by driver’s physiological states, vehicle defects, bad road pavement, and reduced atmospheric visibility.For example, a brake failure is prevented by a crash type-independent countermeasure because such a vehicle defect leads to a number of crashtypes.

Table 3 lists some possible first-level IVHS countermeasures for I/CP crashes which are related to driving task errors. These errors are separated into driver recognition errors, driver decision errors, and erratic actions. The last category includes crash causes or actions that may be amenable only to fully automatic control systems. One exception, though, is a SI/SCP crash involving a police car which can be mitigated by an all-red light phase activator.

I/CP crashes caused by driver recognition errors may be prevented by ***in-vehicle signing*** and ***situation display*** of proximity traffic, as first-level applicable IVHS countermeasures. In-vehicle signing informs drivers of the presence of traffic **control devices ahead,** such as a stop sign or a signal light and its phase. A situation display indicates to a SV driver, waiting to either turn left or cross an intersection, whether vehicles are approaching toward the intersection. These countermeasures are implemented using either autonomous (self-contained within the vehicle) or cooperative systems. For instance, autonomous in-vehicle signing could be accomplished using a video-based system that extracts and recognizes traffic control devices. However, such a system may not be applicable to crashes caused by obstructed vision. An alternative would be to employ a cooperative system where a one-way communication link is established from the roadside to the vehicle in order to provide information on traffic control devices ahead. Moreover, situation display information may be acquired by either autonomous on-board sensors, cooperative POV-SV communications, or cooperative infrastructure-SV communications where POV information is gathered by means of roadside traffic detection devices (e.g., loop detector or radar) used for advanced traffic management systems.

IVHS countermeasures applicable to crashes caused by driver decision errors require a decision-making capability in order to warn the driver of hazardous maneuvers. In order to avoid SI/SCP crashes due to drivers who tried to beat the amber phase, the countermeasure must decide whether the SV can cross the intersection safely before the onset of red light. Necessary data might include vehicle speed, vehicle distance to the stop line, vehicle length, time remaining to red light during the amber phase, and intersection width. Warning systems are also applicable to SVs involved in UI/SCP crashes caused by erroneous judgement of gap/velocity of crossing POVs when the SV driver proceeded to cross the intersection after stopping. In addition to obtaining data on POV's velocity and distance, such systems need information on intersection width and SV's capability in accelerating from zero velocity. Information on the SV's turning capability is also essential in warning systems for LTAP crash avoidance.

SYNTHESIS OF CAUSAL FACTORS

The causal factors of five target crash problems (rear-end, SVRD, backing, lane change, and I/CP) have been determined by an in-depth review of 456 NASS CDS hard copy case reports and 226 GES PARs. In addition, the frequencies of crash types caused by the identified factors were weighted in order to be nationally representative, using ***case*** weights ***equal*** to ***the national inflation factor*** assigned to each case at the end of the data collection year. These national inflation factors are based on crash sampling stratification (injury severity and vehicle characteristics) and on location of the investigative unit. Table 4 lists the weighted percentages of causal factors for four crash types along with four I/CP crash subtypes. The causal factors are arranged in various categories which are amenable to IVHS crash countermeasure concepts at incremental levels of complexity. These categories include driver errors (recognition, decision, and erratic actions), driver physiological impairment, vehicle defects (brake failure, tire blowout, and engine stalled), low-friction roadway surface (wet and icy), and reduced atmospheric visibility. Moreover, the weighted average percentages of each category are computed based on crash type frequencies indicated previously in Figure 1. These crash types accounted for 66.4% of all 1991 crashes. Note that many collisions were attributed to a combination of causes arranged in separate categories; however, only one dominant cause is assigned based on subjective assessment by an expert analyst.

Driver recognition errors were the leading cause of crashes investigated, which include inattention, looked-did not see and improper lookout, internal and external distraction, and vision obstructed by intervening vehicles, roadway geometry, and roadway appurtenances. Applicable, first-level IVHS crash countermeasures include situation display of proximity traffic (backing and lane change), integrated in-vehicle signing and situation display (intersection), headway detection system (rear-end), and lane drift warning system (SVRD). Some crash type-specific countermeasures may apply to other crash types. For instance, the SVRD crash problem involved drivers who steered off the roadway in order to avoid a rear-end crash (7%). Also, inattentive drivers involved in a lane change/merge crash drifted out of their travel lane (3.8%). The former instance indicates that a rear-end crash countermeasure may have prevented the SVRD crashes. The latter instance suggests that had the other vehicle not been present the lane drift countermeasure would have prevented an SVRD crash.

Driver decision errors constituted the second leading cause of target crashes, which consist of drivers who tried to beat a signal/another car, misjudged gap/velocity of approaching vehicles, tailgated a lead vehicle, and drove at excessive speeds. Driver warning systems seem to be the first-level, applicable IVHS crash countermeasures which possess a decision-making capability to aid drivers in their driving task. Examples are safe inter-vehicle gaps (rear-end and lane change), clear straight crossing at signed intersections against cross traffic, available time to pass through signalized intersections, safe left turns, and appropriate vehicle speeds (SVRD and backing). This particular category includes crashes caused by a combination of factors, such as following too closely and driver inattention (19.4%) in rear-end crashes, excessive speed and alcohol (3.9%) in SVRD crashes, inappropriate velocity and improper lookout (% unknown) in backing crashes, and excessive speed and bad pavement conditions (2.2%) in lane change crashes. Driver physiological impairment is the third leading cause (drunk: 5%, drowsy: 3.796, and ill: 4.3%) of the five target crashes. That category is followed by erratic actions category that mostly involves unlawful drivers, unsafe driving acts, and evasive maneuvers. Unlawful drivers are those who deliberately violated signals/signs. Fully automatic control systems seem to be the only applicable IVHS crash countermeasures to both unlawful drivers and unsafe driving acts. Evasive maneuvers were performed by the SV in order to avoid collision with an encroaching POV or crossing pedestrian/animal. For instance, 1.1% of rear-end crashes occurred due to vehicles changing lane in the SV path and 13.7% of SVRD crashes occurred in order to avoid crossing pedestrian/animal (5.8%), head-on crashes (6.5%), and lane change crashes (1.4%). Evasive maneuvers can be avoided if the POVs were equipped with crash avoidance systems. On the other hand, in situations where pedestrians or animals suddenly appear in the SV path, the effectiveness of IVHS crash countermeasures depends on the gap/velocity of the SV when the crossing occurred. Erratic actions also included cases of improper signalling, by the POV. These may be just unavoidable due to misleading driver’s intent.

Table 5 lists IVHS countermeasures applicable to crashes caused by driver state and other elements of the driving environment, which are independent of crash scenarios. For instance, vehicle defects encountered in intersection crashes were brake failures which might be amenable to a brake condition monitor. Crashes caused by wet or icy pavement might be prevented by a pavement condition monitor. Also, other countermeasures would have been applicable such as antilock brakes and systems that advise the driver of a lower, safe speed limit appropriate for the surrounding environmental conditions.

SUMMARY

This paper described a methodology that was employed in the analysis of target crashes to identify crash causal factors and potential IVHS countermeasures, model crash scenarios and avoidance maneuvers, and determine research and data needs. The results of the lane change crash analysis were summarized to illustrate the various steps of this methodology. In addition, preliminary assessment of causal factors and applicable IVHS countermeasure concepts were provided for intersection/crossing path collisions. Finally, the causal factors of five crashes analyzed to date were synthesized and arranged in separate categories that might be amenable to various IVHS countermeasure concepts.

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Table 1: Summary of Modeling Parameters for Proximity Lane Change Crashes

Parameter	Value
Car Width	6ft
Lane Width	12 ft
LATGAP	3 - 9 ft
ILCD	9 - 15 ft
t_{LC}	2 - 16 s
A_r	0.4g 0.55g 0.7g
k	0.4g/s 0.65g/s 0.7g/s

Table 2: Causal Factor Distribution of Intersection/Crossing Path Crashes

Crash Causes	**Intersection Crashes**			
	Straight Crossing Paths		Left Turn Across Path	
	Signalized (37*+13** cases)	Unsignalized (91* cases)	Signalized (110* cases)	Unsignalized (44* cases)
Driver inattention	36.4%	21.8%	1.9%	0%
Looked - did not see	0%	37%	23.9%	25.1%
Vision obstructed:				
intervening vehicles	0.8%	10.7%	17.9%	30.2%
roadway geometry	0%	4.1%	0%	6.4%
roadway appurtenances	3.5%	0.9%	0%	0%
Tried to beat signal/other car	16.2%	0%	5.1%	0%
Misjudged gap/velocity	0%	12.4%	25.4%	37.3%
Improper signalling by POV	0%	0%	2.5%	0.5%
Violation of signal/sign	23.2%	3.2%	22.3%	0%
Hit and run	2.4%	0%	0%	0%
Emergency vehicle	3.5%	0%	0%	0%
Driver intoxicated	12.6%	2.5%	0.4%	0.5%
Vehicle defect (brake failure)	1.6%	0%	0%	0%
Low-friction pavement	0%	7.2%	0%	0%
Reduced atmospheric visibility	0%	0%	0.2%	0%
Total	100.2%	99.8%	99.6%	100%

* NASS CDS cases ** GES PAR cases

Table 3: Applicable, First-Level IVHS Intersection/Crossing Path Crash Countermeasures

Crash Causes		**Intersection Crash Countermeasures**			
		Straight Crossing Paths		**Left Turn Across Path**	
		Signalized	**Unsignalized**	**Signalized**	**Unsig.**
Driver Recognition Errors	**Driver inattention**	***In-vehicle signing*:** **Signal ahead & light status indicator**	***In-vehicle signing*:** **Stop sign ahead indicator**	***Situation display*:** Crossing car indicator	
	Looked - did not see		***Situation display*:** **Crossing car indicator**		
	Vision obstructed: interviewing vehicles roadway geometry ***roadway appurtenances***	***In-vehicle signing*:** **Signal ahead & light status indicator**	***In-vehicle signing* and *situation display***		
Driver Decision Errors	**Tried to beat signal/ other car**	***Warning system*:** **Amber phase crossing decision-making**		***Warning system*:** **Left turn decision-making**	
	Misjudged gap/velocity		***Warning system*:** **Straight crossing decision-making**		
Erratic Actions	**Improper signalling (POV)**			**none**	
	Violation of signal/sign	***Fully automatic control*:** **Automatic braking if red & amber? lights**	***Fully automatic control*:** **Automatic braking system**	***Fully automatic control*:** **Automatic braking system**	
	Hit and run				
	Emergency vehicle	***All-red phase activator***			

Table 4: Causal Factor Distribution of Eight Target Crash Types and Subtypes

Crash Types	**Causal Factors**								
	Recognition Errors	Decision Errors	Erratic Actions	Alcohol	Drowsy & Ill	Vehicle	Roadway	A.V.*	Total
Rear-End	56.7%	26.9%	1.1%	2.1%	9.6%	1.2%	2.3%	0.1%	100.0%
SVRD	15.5%	17.8%	15.9%	10.1%	15.2%	5.2%	20.2%	0%	99.9%
Backing	60.8%	26.6%	2.0%	3.0%	1.9%	5.7%	0%	0%	100.0%
Lane Change	65.0%	32.1%	2.6%	0%	0%	0.3%	0%	0%	100.0%
SI/SCP	40.7%	16.2%	29.1%	12.6%	0%	1.6%	0%	0%	100.2%
UI/SCP	74.5%	12.4%	3.2%	2.5%	0%	0%	7.2%	0%	99.8%
SI/LTAP	43.6%	30.5%	24.8%	0.4%	0%	0%	0%	0.2%	99.5%
UI/LTAP	61.6%	37.3%	0.5%	0.5%	0%	0%	0%	0%	99.9%
Weighted Average	44.6%	22.2%	8.9%	5.0%	8.0%	2.2%	7.9%	0.0%	98.8%

A.V. = Atmospheric Visibility

Table 5: Applicable First-Level, Type-Independent NHS Crash Countermeasures

Crash Causes		Countermeasures
Driver State	Driver intoxicated	*Impaired driver monitor*
Vehicle	Vehicle defects	*Component status monitor*
Road Surface	Low-friction pavement	*Pavement condition monitor*
Weather	Reduced visibility	*Vision enhancement system*

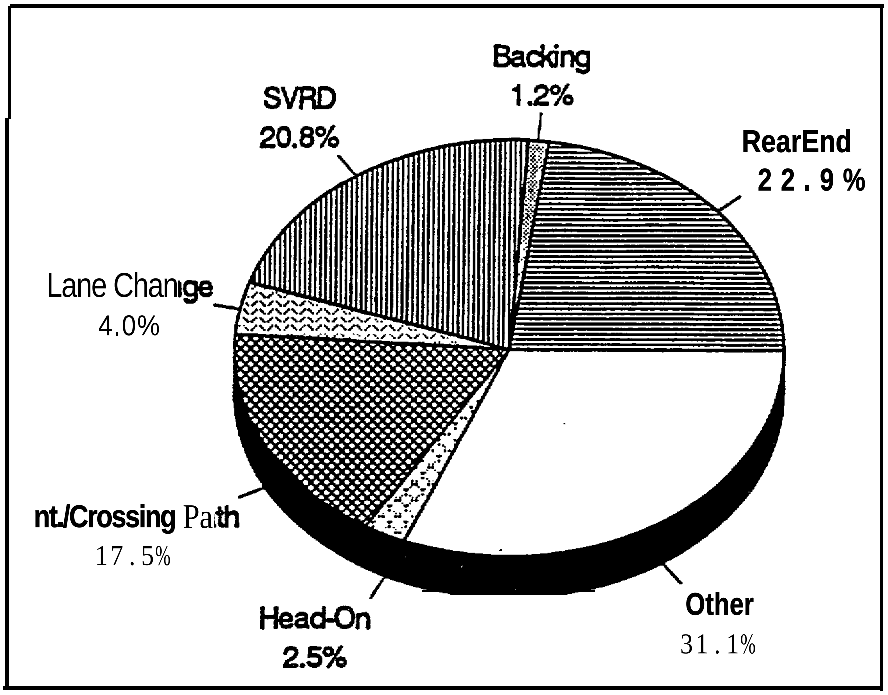

Figure 1: Relative Problem Sizes for Six Target Crash Types (1991 GES)

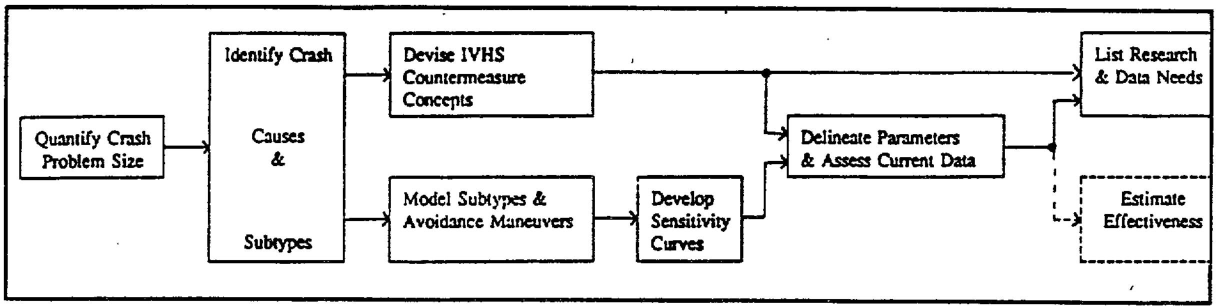

Figure 2: Block Diagram of Crash Problem Analysis Methodology

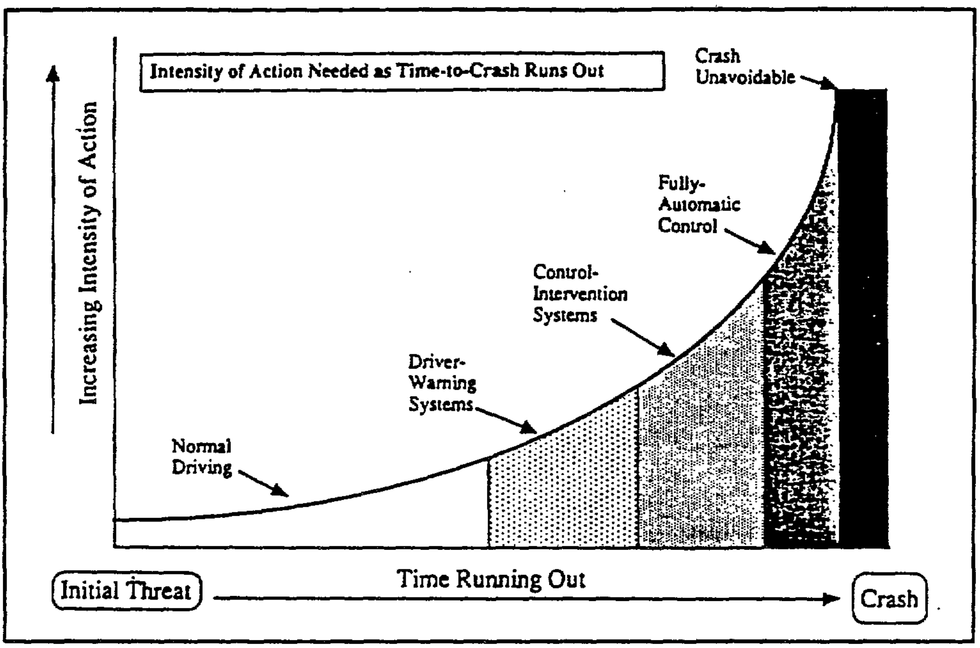

Figure 3: Time-Intensity Graph of Pre-Crash Avoidance Requirements

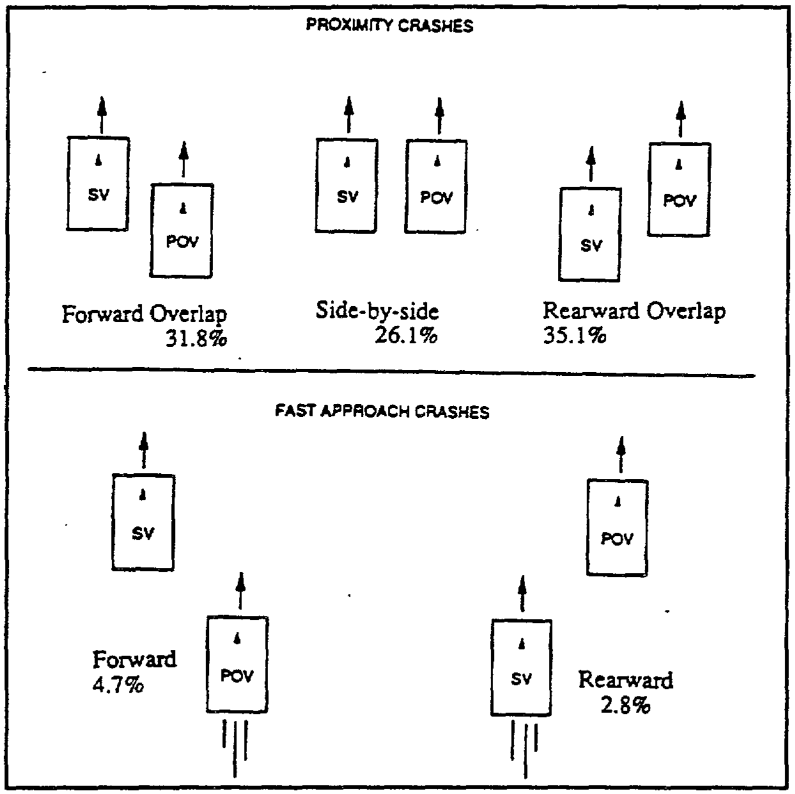

Figure 4: Distribution of Lane Change Crash Subtypes and Variations

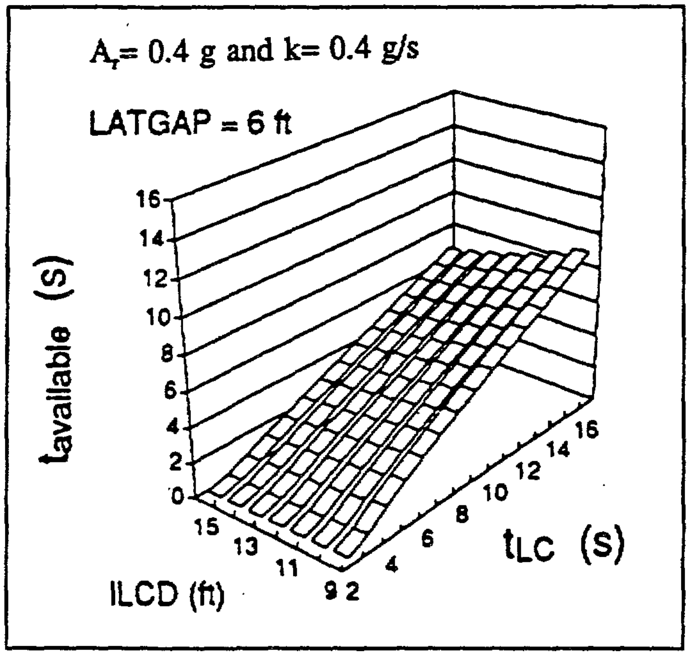

Figure 5: Time Curves to Avoid Proximity Lane Change Crash Subtypes