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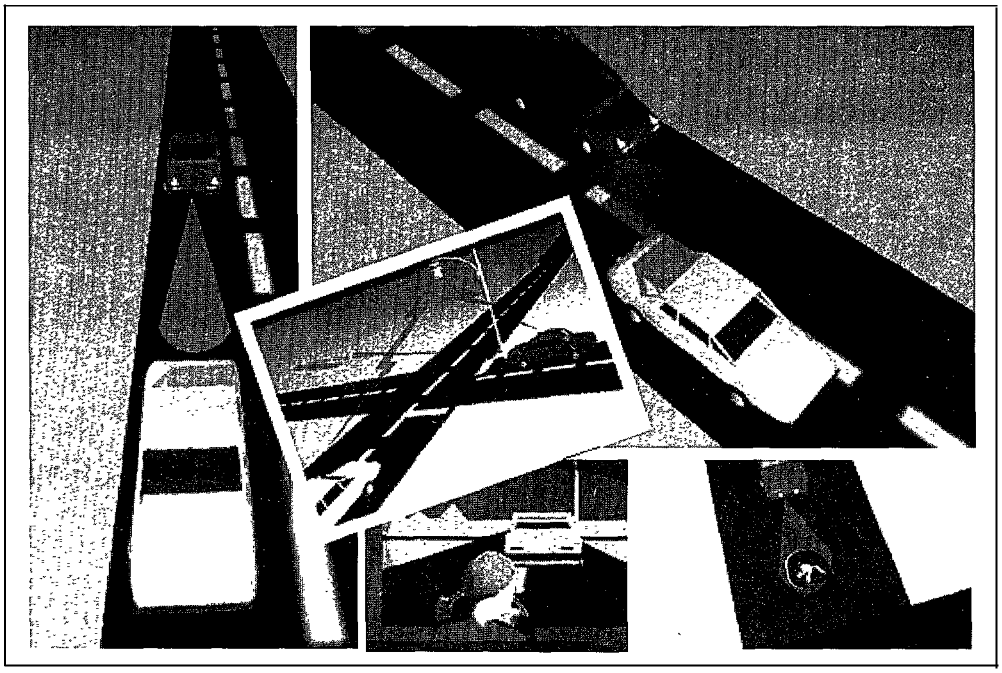

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This report provides a preliminary analysis of reduced visibility crashes to support the development of crash avoidance system (CAS) concepts as part of the Intelligent Vehicle Highway System (IVHS). In this report, a reduced visibility crash is defined and background on driver perception is presented in order to identify candidate sources of visibility limitations and enhancements. Some indications as to the size of the reduced visibility problem are presented. A detailed analysis of a sample of crashes is discussed to provide further insights into the nature of the problem. Candidate functional crash avoidance concepts are presented in terms of in-vehicle warning systems, roadway information systems, direct vision enhancement systems, and imaging vision enhancement systems. The mechanisms of reduced visibility and how it affects stopping sight distance are then presented together with recommended sight distances used in traffic engineering for highway safety. The analysis concludes with a list of research needs that will further an understanding of driver vision and perception requirements and the development of effective reduced visibility crash countermeasures.

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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 (Volpe Center), has a multidisciplinary program underway to identify crash causal factors and applicable Intelligent Vehicle Highway System (IVHS) countermeasure concepts; model crash scenarios and avoidance maneuvers; provide preliminary estimates of countermeasure effectiveness when appropriate; and identify research and data needs.

Under this program, nine target crash types are examined, including the following:

- Rear-End
- Backing
- Single Vehicle Roadway Departure
- Lane Change/Merge
- Signalized Intersection, Straight Crossing Path
- Unsignalized Intersection, Straight Crossing Path
- Intersection, Left Turn Across Path
- Reduced Visibility (Night/Inclement Weather)
- Opposite Direction

This report presents the results of the reduced visibility crash study. The results are based on the analysis of 250 cases that were selected from the 1992 Crashworthiness Data System (CDS). The crashes analyzed in this report were weighted for severity so that they might more closely approximate the national profile.

The authors of this report are Louis Tijerina, Nathan Browning, Edwin F. Madigan, and Susan J. Mangold of Battelle, and John A. Pierowicz of Calspan.

Mark Mironer of the Volpe Center served as the technical monitor for this report. John Hitz, Joseph S. Koziol, Jr., and Wassim Najm of the Volpe Center; William A. Leasure, Jr., Ronald R. Knipling, Michael Perel, and August L. Burgett of the National Highway Traffic Safety Administration Office of Crash Avoidance Research (NHTSA OCAR) provided technical guidance and reviewed this report.

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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

^{o}F	-40°	-22^{0}	-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 is a list of abbreviations and acronyms used in this report, and their definition.

a	braking acceleration, ft/s2
ANOVA	analysis of variance approach
B_B	background luminance, foot-lamberts
B_T	target luminance, foot-lamberts
B_v	veiling luminance caused by glare sources or backscatter brightness, foot-lamberts
C_D	apparent contrast to the observer at distance D
C_o	inherent contrast between target and background
c	contrast, the relationship between target and background
CAS	crash avoidance system
CIE	Commission Intemationale de L'Eclairage
CCD	charge-coupled device
o	attenuation or extinction coefficient of the intervening medium, l/ft
D	distance to target, ft
DGF	Discomfort Glare Factor, proportion
D_0	initial separation distance, ft
$D_{min\ stop}$	minimum required stopping distance, ft
D_{stop}	total stopping distance, ft
DUI	driving under the influence
DVES	Direct Vision Enhancement System
e	the base of the natural system of logarithms, 2.71828
FACS	fully automatic control systems
FARS	Fatal Accident Reporting System
FLIR	forward-looking-infrared
GES	General Estimates System
GPS	global positioning system
HUD	head-up display
IES	Illuminating Engineering Society
IP	instrument panel
IVES	Imaging Vision Enhancement System
IVHS	Intelligent Vehicle Highway System
NASS CDS	National Accident Sampling System Crashworthiness Data System
NHTSA	National Highway Traffic Safety Administration
PARs	police accident reports
PDR	perception-decision-response
PCDETECT	computer sight distance program implementing the effect of luminance on contrast reduction
PR	police reported
$RCS(B_B)$	relative contrast sensitivity of a driver adapted to background luminance proportion

s v	subject vehicle
t_d	time due to driver and system delays, s
UV	ultraviolet
V	travel velocity, ft/s
SVI	Visibility Index, given as apparent contrast
VI/FOG	Visibility Index with modifications for fog conditions
VMS	variable message sign

EXECUTIVE SUMMARY

This report provides a preliminary analysis of reduced visibility crashes to support development of crash avoidance system (CAS) concepts as part of the Intelligent Vehicle Highway System (IVHS). A reduced visibility crash is defined here as interference, caused by low light or obscurance, with the capability of the road, other vehicles, or potential obstacles (including pedestrians) to stand out in relation to their backgrounds so as to be readily detected by a driver. Reduced visibility applies to both day and night conditions and to conditions of fog, dust, rain, snow or other atmospheric obscurants.

The driver's visual tasks basically involve target detection and perception along with a decision-making step and subsequent response that together comprise the Detection-Perception-Decision-Response sequence. This sequence accounts for the driver delay time that must be accommodated by CAS concepts. Object visibility depends on many factors, especially the object angular size at the driver's eye and apparent object-background luminance contrast. Angular size is a function of actual size, distance, and orientation of the driver to the object. Contrasts are related to object and background luminance and reflectance, ambient lighting, and atmospheric obscurants such as rain, fog, snow, dust, and smoke. The bigger the object, the less the contrast needed for detection, all else being equal. Conversely, the lower the apparent contrast, the larger the required visual angle for detection, i.e., a driver must be closer to an object or potential obstacle for detection. Without sufficient contrast it does not matter how big an object is. The human visual system also plays a role in determining an object's visibility. The rod and cone systems of the eye and ambient and focal modes of perception are differentially affected by reduced ambient illumination, a primary reduced visibility condition.

The 1991 General Estimates System (GES) indicates approximately 43 percent of all police-reported (PR) crashes occurred in reduced visibility conditions that include non-daylight (dark, dark but lighted, dawn, or dusk) and bad weather (rain, sleet, snow, fog, or smog) conditions. Analysis of the GES database only indicates crash circumstances. Defining the scope of reduced visibility crashes is difficult due to concomitant factors such as loss of traction during conditions of obscurance from rain or snow and fatigue during levels of low-ambient illumination. A more in-depth analysis is needed and the Indiana Tri-Level study provides a good starting point. This analysis revealed very few crashes (at most, one-half of 1 percent of all crashes analyzed) that could be identified as probably or certainly related to reduced visibility. It is possible that vision enhancement to support crash hazard recognition (reported by as definitely or probably involved in up to 56 percent of the crashes analyzed) may be the most profitable route for CAS development. A more recent analysis of Fatal Accident Reporting System (FARS) cases reported between 1980 and 1990 attempted to assess the role of nighttime reduced visibility in traffic mishaps. This analysis suggests that nighttime reduced visibility bears little relationship to nonpedestrian/pedalcyclist accidents, but is a major factor in accidents involving pedestrians and pedalcyclists. As a point of reference, the 1992 GES indicated less than 1 percent of police reported crashes involved pedestrians or pedalcyclists in reduced visibility conditions.

In order to further characterize the reduced visibility problem, a detailed clinical analysis found 53 crashes that are probably or possibly caused by reduced visibility conditions. Unfortunately, case numbers and weights were not recorded to support an estimate of the size of the reduced visibility problem in relation to the universe of crashes. However, using crash severity to weight cases in the clinical sample, 62 percent of such cases did not involve an attempted avoidance maneuver. In these cases, the driver either did not realize that a collision was impending or did not have enough time to respond once it was realized. An investigation of crash types suggests two major categories of reduced visibility crash types: roadway departures and various crashes involving other vehicles, primarily due to hazard detection failures. Roadway departures are events in which lateral control of the vehicle is not maintained within the specified boundaries of the roadway. Hazard detection failures involve striking an obstacle in the road. This is the larger category and includes head-on collisions, rear-end collisions, and turns across path. Neither category includes crashes that occur as the result of collision-avoidance maneuvers. Fundamentally, these two categories of reduced visibility crashes reflect an inability of the driver to adequately see lane markings and signs, and to detect objects. Thus, reduced visibility crashes may be alleviated by systems that compensate for the drivers's inability to see adequately.

Candidate functional crash countermeasure concepts are organized in accordance with four major categories: in-vehicle warning systems, roadway information systems, direct vision enhancement systems, and imaging vision enhancement systems. In-vehicle warning systems warn the driver in response to the detection of a possible roadway deviation or other crash hazard and include headway detection, near-object detection, and lane monitoring systems. Roadway information systems for reduced visibility crash avoidance include concepts such as in-vehicle signing, variable message signs (VMS), and shoulder rumble strips. In-vehicle signing provides a display in the vehicle for traffic advisories. VMS can alert the driver to poor visibility conditions ahead and indicate a reduced travel speed that is appropriate to the driving conditions. Rumble strips mounted on the shoulder of the roadway have proven useful for alerting distracted or drowsy drivers and may prevent at least some reduced visibility-related roadway departures. Direct vision enhancement systems (DVES) include ultraviolet (UV) headlights, polarized headlights, and enhanced taillight systems. This class of countermeasures enhances the visibility of objects directly to the driver's naked eye. On the other hand, imaging vision enhancement systems (IVES) use various sensors, illuminators, processors, and driver displays to provide a sensor-based image of the driving scene superior (in principle) to that available with direct vision. These images can be presented via either an in-vehicle video display or a head-up display (HUD).

IVES, perhaps the most frequently mentioned reduced visibility crash countermeasure, require additional research on sensor technology, sensor data processing, and driver interface design before such systems will be viable for cars and trucks. Sensor technology R&D faces the challenge of dealing with reduced ambient illumination and all types of weather while achieving a low enough device cost to ensure positive cost benefits. Studies reviewed indicate, for example, that infrared sensors are not useful in snow or rainfall due to the low contrasts coming from wet objects and may have a visibility range lower than that available to direct vision in haze and fog conditions. On the other hand, infrared imaging may be well-suited to night conditions if the information can be displayed to the driver adequately. IVES in-vehicle displays may compete with the driver's attention to the driving scene, may not provide adequate information for vehicle control, and may not adequately support various driving maneuvers because of restricted ability of the displayed information (especially on small screen displays) to convey target presence, distance, or speed. Contact-analogue HUDs superimpose symbology over the real objects they represent. Such displays may be unacceptable due to time delay between the sensor image overlay with the real-world object, vibration-induced image degradation, contrast reduction of directly perceived road scene objects, and difficulties in driver interpretation of the sensor image.

The mechanisms of reduced visibility and how it affects stopping sight distance are presented. The effect of a uniform atmospheric distribution of suspended particles under daylight conditions contrast reduction along a horizontal field of sight is represented by Koschmeider's Law and is reviewed. A model called Visibility Index/FOG (VI/FOG) was found that attempts to integrate atmospheric effects on contrast with data on human contrast thresholds. Reduction in contrast due to changes in illumination are examined with a more comprehensive implementation of Blackwell's threshold contrast curves in a headlamp seeing distance model, PCDETECT. An example of the effect of a shortened stopping sight distance caused by reduced visibility is given. This example illustrates that stopping distance is made up of distance after the driver sights an object and begins braking, plus the distance traveled during braking to a stop. Because the latter component is fixed (assuming equal braking deceleration), reduced sight distance shortens the maximum time available for driver and machine delays. Finally, various sight distance values used in traffic engineering are included to indicate desirable vision enhancement system ranges. Given the variety of crashes in which reduced visibility is involved, a system range of about 1,600 ft of sight distance would be preferred to cover many circumstances and highway travel speeds. A system range of less than 125 ft of sight distance is likely to be ineffective.

This analysis concludes with a set of research needs. There is a need to better understand the scope and nature of the reduced visibility problem. To clarify these points, statistical models that assess the relative contribution of reduced visibility and other factors present in nondaylight and bad weather conditions would be instructive. Further assessment of crash problems not represented in the current clinical sample (e.g., pedestrian mishaps, animal strikes) might provide additional insights into reduced visibility crashes. A model that integrates the effects of low-ambient illumination with atmospheric obscurants using recent advancements in visual science would be helpful for estimating visibility ranges in automotive applications and in the design of a sensor system for reduced visibility crash avoidance. Assessing the necessary and sufficient visual information the driver needs for crash avoidance, vehicle control, and maneuvers is considered an important research need. Evaluating the secondary consequences of reduced visibility countermeasures (e.g., increased travel speeds, violation of expected driver behaviors on the part of other road users not equipped with such systems) should be part of any comprehensive evaluation program. Workload effects of in-vehicle imaging displays may be unacceptable and should be investigated, as should driver acceptance of such systems. Sensors and sensor processing technologies need to be developed to perform in a broad range of conditions (night, bad weather) at reasonable cost. It is also clear that acceptable means to display the sensed information to the driver is needed. This includes addressing the viability of in-vehicle image displays and HUDs. Research should focus on the necessary and sufficient design parameter values for driver displays in terms of display resolution, display size, field of view and range, displayed target size, and so on. HUD technology for vision enhancement systems also require further research into their effects on driver performance and acceptability, especially in regard to driver situational awareness of the driving situation, workload, and effects of sensor image overlays on crash avoidance and driving task performance. At present, it appears that imaging vision enhancement systems, though perhaps most frequently mentioned in the trade literature as a solution to night/all weather driver visual support, face significant research and development challenges to achieve implementation in IVHS in the near term.

1. BACKGROUND

1.1 INTRODUCTION

This report provides a preliminary analysis of reduced visibility crashes to support the development of crash avoidance system (CAS) concepts as part of the Intelligent Vehicle Highway System (IVHS). In this report, a reduced visibility crash is defined and background on driver perception is presented in order to identify candidate sources of visibility limitations and enhancements. Some indications as to the size of the reduced visibility problem are presented. A detailed analysis of a sample of crashes is discussed to provide further insights into the nature of the problem. Candidate functional crash avoidance concepts are presented in terms of in-vehicle warning systems, roadway information systems, direct vision enhancement systems, and imaging vision enhancement systems. The mechanisms of reduced visibility and how it affects stopping sight distance are then presented together with recommended sight distances used in traffic engineering for highway safety. Finally, this analysis concludes with a list of research needs that will further an understanding of driver vision and perception requirements and the development of effective reduced visibility crash countermeasures.

1.2 DEFINITION OF REDUCED VISIBILITY CRASHES

Reduced visibility influences on driver performance can assume a variety of forms. The driver may briefly deviate from the road after losing sight of the roadway edge. Pile-ups may occur that involve dozens of cars colliding in the fog, with the resulting loss of life, serious injury, and financial costs. The objective of the current project is to provide an overview of the problem of reduced visibility, identify why driving problems may occur, and discuss some preliminary approaches to minimizing the impact of reduction in visibility.

Like many complex factors, reduced visibility can be defined in a variety of ways. Reduced visibility is defined here as:

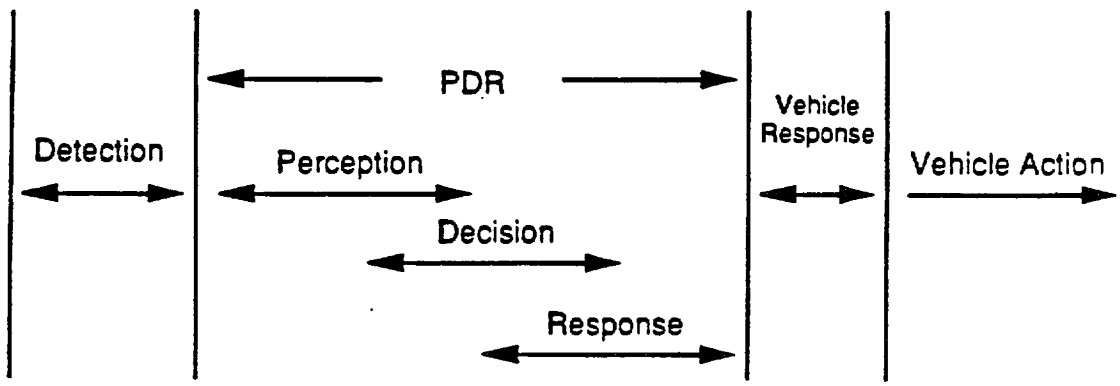
> *Interference, caused by low light or obscurants, with the capability of the road, other vehicles, or potential obstacles to stand out in relation to their backgromds so as to be readily detected by a driver.*

With respect to viewing conditions, reduced visibility is assumed to occur under both daylight and nighttime conditions. It is then possible to make comparisons as to the severity of visibility conditions, such as nighttime fog versus daytime fog. Finally, visibility of a variety of objects is considered, including the detection of obstacles, lane markings, road geometry, and signs. A complete model of reduced visibility must be capable of addressing the range of relevant information sources.

In simplest terms, the driver's visual requirements involve target detection (registering that something is present), recognition (being aware that the something is of a particular class, such as a vehicle, pedestrian, roadway marking, signage, and so on), and identification (picking up sufficient information to determine what driver action, if any, is required). Generally, detection must occur before recognition and identification are possible. Collectively, the detection-recognition-identification process is referred to as target acquisition (Boff and Lincoln, 1988). This process supports driver decisionmaking on what action should be taken by the driver (e.g., do nothing, take one's foot off the accelerator pedal, brake, steer away, etc.). Finally, there is a response-execution stage in which the driver makes the necessary steering and pedal inputs to put the decision into effect. Since this sequence unfolds over time, activities depicted in Figure l-1 make up the driver reaction time delay that CAS concepts must accommodate, along with the kinematic requirements of the avoidance maneuver.

Object visibility is a function of many factors (see Table l-l). Of these, object visibility is fundamentally proportional to object angular size and apparent object-background luminance contrast (Boff and Lincoln, 1988). Angular size is a function of distance and orientation between object and viewer. Apparent contrast is a function of ambient lighting (such as nighttime driving) and the presence of obscurants in the air (such as driving in fog, dust, or rain). As a first approximation, the bigger the object, the less the contrast needed for detection, all else being equal. Conversely, the lower the apparent contrast, the larger the visual angle must be for target detection; this is directly related to separation distance between the driver and a potential obstacle or other object. Without sufficient contrast, it does not matter how big an object is.

In nighttime driving (Olson and Sivak, 1984), some objects are more reflective in headlighting than others; this depends on the contrast between the object (e.g., a person, a pavement marking, or a vehicle) and its background (e.g., the sky, pavement, roadside appurtenances). In general, the object must be less or more bright than the background in order for detection to occur. An object cannot be seen without contrast, regardless of size; however, a larger object usually has a lower threshold contrast than a smaller object for equally likely detection. A lack of uniform illumination may complicate this process, as will poor reflectance of the object and the background material. Olson and Sivak point out that, in driving situations, the same object will often be of variable contrast. In their example, a pedestrian's legs may be seen against a background of road or shoulder surface while the upper portion will be seen against a background of more distant and less illuminated portions of the background. Given that most objects and backgrounds in driving are not homogenous, these variations can serve at times to camouflage the object. In a later section of this report, the concept of threshold contrast will be examined in the context of seeing distances or visibility sight distances.



PDR means Perception-Decision-Response.

Detection involves registering that something is present.

Perception involves target recognition and identification. It begins after detection is affected by the nature of the stimulus and driver expectancy.

Decision is the development and evaluation of alternative responses.

Response involves the driver's inputs to the vehicle controls once a decision is made.

Vehicle Response is the time lag between driver response to controls and the initiation of vehicle action.

Vehicle Action is affected by vehicle characteristics such as steering sensitivity, condition of brakes, pavement characteristics, tire conditions, and vehicle speed.

Figure 1-1. Detection-Perception-Decision-Response Sequence (Source: Adapted from Tijerina, Hendricks, Pierowicz, and Kiger, 1993.)

Table l-l
Factors Affecting Object Visibility

Factors Affecting Object Visibility	Definition of Terms	Associated Reduced Visibility Countermeasures
Contrast between object and background	Contrast is the luminance relationship between an 0bject and its background.	Contrast enhancement
Object visual size	Visual size is the angle the object subtends at the eye.	Size enhancement
Adaptation, including transient adaptation	Adaptation is the change in visual sensitivity due to increased or decreased levels of light; transient adaptation is adaptation to different luminance levels caused by shifting fixation between surfaces.	Luminance control of visual scene within vehicle
Disability glare	Disability glare is luminance greater than that to which the eye is adapted which results in reduced visual performance.	Luminance filtering
Scene complexity (camouflage)	Camouflage is the disguising of an object to make it indistinguishable from its surroundings.	Highlighting targets from background
Object color, shape, reflectance	Reflectance is the proportion of light that falls upon an object that is reflected.	Unknown for color, shape. Selective highlighting by reflectance.
Expectancies and alerting	Expectancies are anticipated states, objects, or events; Alerting is making aware to meet some danger or emergency.	Orienting display (visual, auditory, tactile)
Driver individual differences (e.g., age, object/scene familiarity, fatigue, stress, etc.)	Individual differences are differences across drivers or within a driver at different times that can affect performance.	Driver-specific display settings
Motion dynamics (optical flow variables)	Optical flow variables are variables that indicate self motion from the change of position over time of points that make up the visual field.	Enhance/modulate optical flow variables
Object familiarity	Familiarity is the acquaintance with objects or events.	Unknown

Consider next the effects of atmospheric obscurants. Particles in the atmosphere most typically include rain droplets, fog, and snow. Less often, dust or smoke also reduce visibility. These particles in the air reduce contrast by means of backscatter and absorption (Frenk, Skaar, and Tennant, 1972). Fog consists of micro droplets that act like lenses and scatter headlight illumination, thus reducing light reaching objects in the driving scene, lighting up the intervening atmosphere, and reducing contrast. Olson and Sivak (1984) point out that rain droplets:

- Act as lenses to produce optical distortion and accentuate glare;
- Mix with residue on windshields that light up when facing oncoming headlights, thereby reducing apparent contrast of the road scene;
- Reduce the reflective properties of pavement markings like edge lines; and
- Fill in irregularities in the road surface to create road glare and reduce road visibility; but
- May enhance the visibility of reflectorized road signs by reflected light from wet road surfaces, or providing sheen (glistening brightness) to objects because the background does not brighten up as rapidly as when the pavement is dry.

Mathematical expressions for apparent contrast reduction due to atmospheric attenuation can be specified (Kaufman, 1981; Middleton, 1958), but estimates of visibility in a specific condition are difficult to make (Olson and Sivak, 1984). The effects of smoke, dust, and smog presumably follow similar patterns of backscatter and absorption, while snow and fog may more closely resemble the effects of rain,

The nature of the human visual system also plays a part in reduced visibility crashes. For example, the eye consists of cones and rods. The cones are concentrated in the center of the retina (the fovea), require relatively high levels of illumination, and process visual details with high visual acuity in color. These are thought to be the principal receptors used for object detection and identification. On the other hand, rods are more numerous, are located in the retinal periphery, work well under low illumination as well as high, and process motion cues with relatively low acuity in black and white.

Liebowitz (1988) has noted studies that indicate that the speeds at which drivers drive in night conditions are not substantially different than the speeds used under daytime lighting. However, crash rates are much higher at night (adjusting for traffic volume differences) for a variety of crash types (Ward, Stapleton, & Parkes, 1994). Liebowitz & Owens (1986) proposed that two modes of visual processing account for this seemingly illogical behavior. Visual guidance of motion requires relatively little attention and is supported primarily with the rods; this is termed ambient vision. On the other hand, identification and recognition of a hazard requires visual attention and is supported primarily by the cones; this is termed *focal vision*. Since the driver suffers little degradation in the vision needed for spatial orientation and visual control of motion at night, there is no apparent need to slow down. The degradation in focal vision is less apparent; therefore, drivers tend to overdrive their headlights. Additionally, adaptation to oncoming headlights and glare is much more disruptive to focal vision than to ambient vision. In particular, disability glare caused by oncoming headlights raises the required contrast to detect objects for some time. This becomes more pronounced with older drivers, as do a number of visual defects (Olson, 1993). Section 5 of this report discusses the most basic mechanisms of reduced visibility and how they affect sight distance. Before that, however, it is useful to examine the size of the reduced visibility problem, circumstances surrounding it, and reduced visibility countermeasure concepts that may prove useful for crash avoidance.

2. PROBLEM SIZE

2.1 PROBLEM OVERVIEW

Mass databases, such as the General Estimates System (GES), only support general inferences on the role reduced visibility plays in crash occurrence. Unlike other reports analyzing different crash types (e.g., Knipling, et al., 1993; Tijerina et al., 1994; Chovan et al., 1994), reduced visibility crashes are not a distinct type of crash, but rather a collection of different crashes with a common contributing factor – reduced visibility. As such, defining the scope of the problem is difficult.

One way to begin is to assess the proportion of crashes that occur under conditions of reduced visibility. GES data from 1991 indicate that approximately 43 percent of police-reported (PR) crashes occurred under conditions of reduced visibility. These included crashes that occurred in nondaylight conditions (dark, dark-but-lighted, dawn, or dusk) and in bad weather (rain, sleet, snow, fog, or smog). These are only crash circumstances, not causal factors per se. The difficulty in estimating the size of reduced visibility crashes comes from the many other factors that are also at play under these conditions. For example, non-daylight conditions confound low-ambient illumination with driver fatigue and a higher incidence of driver intoxication. Bad weather confounds reduced visibility with reduced traction. Therefore, it is unlikely that mass databases can support a good estimate of reduced visibility crash incidence. The concept of partitioning other crash causal factors, perhaps by means of covariance analysis, merits further investigation.

A more in-depth analysis of reduced visibility's role in crashes is provided in the Indiana Tri-Level Study (Treat, Trumbas, McDonald, Shinar, Hume, Stansifer, & Castellan, 1979). The study's name comes from the fact that crashes in the Monroe County, Indiana study area were examined at three levels of depth. Level A involved baseline data collection based on police reports and other sources. Level B involved on-site teams of technicians who responded to accidents at the time of their occurrence and interviewed drivers, inspected involved vehicles and the driving environment, took photographs of the crash scene, and measured skid marks and other physical evidence. Level C involved further in-depth investigations of a subset of crashes by a multidisciplinary team of behavioral scientists, automotive engineers, accident reconstruction experts, and an environmental data collection aide, among others.

In assessing the causes of crashes, the analysts used an ordinal scale to indicate whether a causal factor assignment was definite, probable, or possible. At most only 0.5 percent of the crashes assessed in-depth by the Tri-Level Study team could be definitely or probably attributed to reduced visibility.

More recently, Owens and Sivak (1993) have attempted to assess the role of reduced visibility in nighttime road fatalities by analysis of cases reported in the Fatal Accident Reporting System (FARS) from 1980 through 1990. In one analysis, they analyzed 104,335 accidents (the term used in FARS) that occurred during morning and evening time periods, called Twilight Zones, during which natural illumination varied systematically in conjunction? with the annual solar cycle. Fatal accidents were over-represented in the darker portions of the Twilight Zones, independently of alcohol consumption, time of day, or day of week. Reduced visibility was a more dominant factor in fatal pedestrian and pedalcyclist accidents than alcohol consumption, while the reverse was true for non-pedestrian and pedalcyclist accidents. In a second analysis, seasonal variation in lighting was assessed via analysis of 337,726 accidents recorded between 1980 and 1990 during three time periods: Twilight Zones, Daylight, and Darkness. While the occurrence of nonpedestrian accidents showed little relation to ambient illumination from natural sources, ambient illumination was a major factor in accidents involving pedestrians and pedalcyclists. This was taken to indicate the success of appropriate regulations, lighting systems, and reflective materials on vehicles and fixed roadside obstacles.

2.2 DISCUSSION

Assessment of the size of the reduced visibility crash problem is difficult due to the presence of other factors often present in reduced visibility conditions such as fatigue, alcohol use, and poor traction. While such analyses as those done by Owens and Sivak (1993) merit independent verification, the results suggest that reduced visibility crashes may predominantly involve pedestrians, joggers, or pedalcyclists. Animal strikes might also be considered as part of this problem. To bring these results into perspective, some statistics on the number of pedestrian-related police-reported crashes might be informative. Based on the 1992 GES, there were approximately 85,000 pedestrian-related crashes, of which about 42 percent occurred in nondaylight conditions. In addition, there were approximately 71,000 pedalcyclist police-reported crashes in 1992 according to GES statistics, and only 20 percent occurred in nondaylight conditions. Given that there were roughly 6 million police-reported crashes in 1992, the percentage of nondaylight (i.e., reduced visibility) crashes associated with pedestrian and pedalcyclist mishaps amounts to less than 1 percent of all police-reported crashes.

It is possible that the more central processes of identification, decision, and response execution are the key sources of driver-related problems. Treat, et al. (1979) indicate that between 41.4 and 56.0 percent of the in-depth crash investigations indicated certain or probable recognition errors that include both perception and comprehension problems. If so, then visibility enhancement might be profitably directed toward supporting the recognition and decision phases of driver vision.

3. ASSESSMENT OF REDUCED VISIBILITY CRASH CIRCUMSTANCES

3.1 CLINICAL ASSESSMENT OF DETAILED CRASH CASES

The reduced visibility data set used in this report consists of 97 cases drawn from the 1993 National Accident Sampling System Crashworthiness Data System (NASS CDS) file. Figure 3-l illustrates the methodology used to choose this sample. The initially reviewed sample consisted of approximately 1500 police accident reports (PARs) from the first and second quarter file at the Calspan NASS CDS Zone Center. While many different criteria can be used to identify likely cases for reduced visibility effects, these cases were screened for accident time-of-day (between 21:00 and 06:00 hours) or adverse weather conditions (rain, snow, or fog). Only through review of the data in the PARS could weather conditions at the time of the accident be determined. Based upon these criteria, 250 cases were selected for further analysis.

The NASS CDS hard copy cases pertaining to the PARS were reviewed to determine the selection of the final sample. Of the 250 cases, 153 were eliminated because they did not contain driver comments that might indicate an inability to see, insufficient time to respond, drowsiness, and so on. Comments of the drivers acquired through the NASS interview process were used to determine the applicability of the case to the reduced visibility problem. The rules used to select the sample is shown in Table 3- 1. A case was classified -as ***improbable*** if it involved Driving Under the Influence (DUI), driver fatigue, or other extraneous factors (i.e., not directly related to reduced visibility due to atmospheric obscurants). A case was classified as ***possible*** if it occurred under night or adverse conditions and no DUI, fatigue, or other extraneous factors were involved. A case was classified as *probable* if, in addition to meeting the criteria for a possible case, the driver also stated an inability to observe, or had insufficient time to respond to, an object or event.

3.2 ASSESSMENT RESULTS

Of the total of 97 cases, 44 were classified as improbable, 17 as possible, and 36 as probable. Unfortunately, case numbers and weights were not recorded to support an estimate of the size of the reduced visibility problem in relation to the universe of crashes. However, it is known that NASS CDS cases are generally more severe than GES police-reported crashes. Therefore, percentages within the clinical sample are weighted by severity as described in Appendix A.

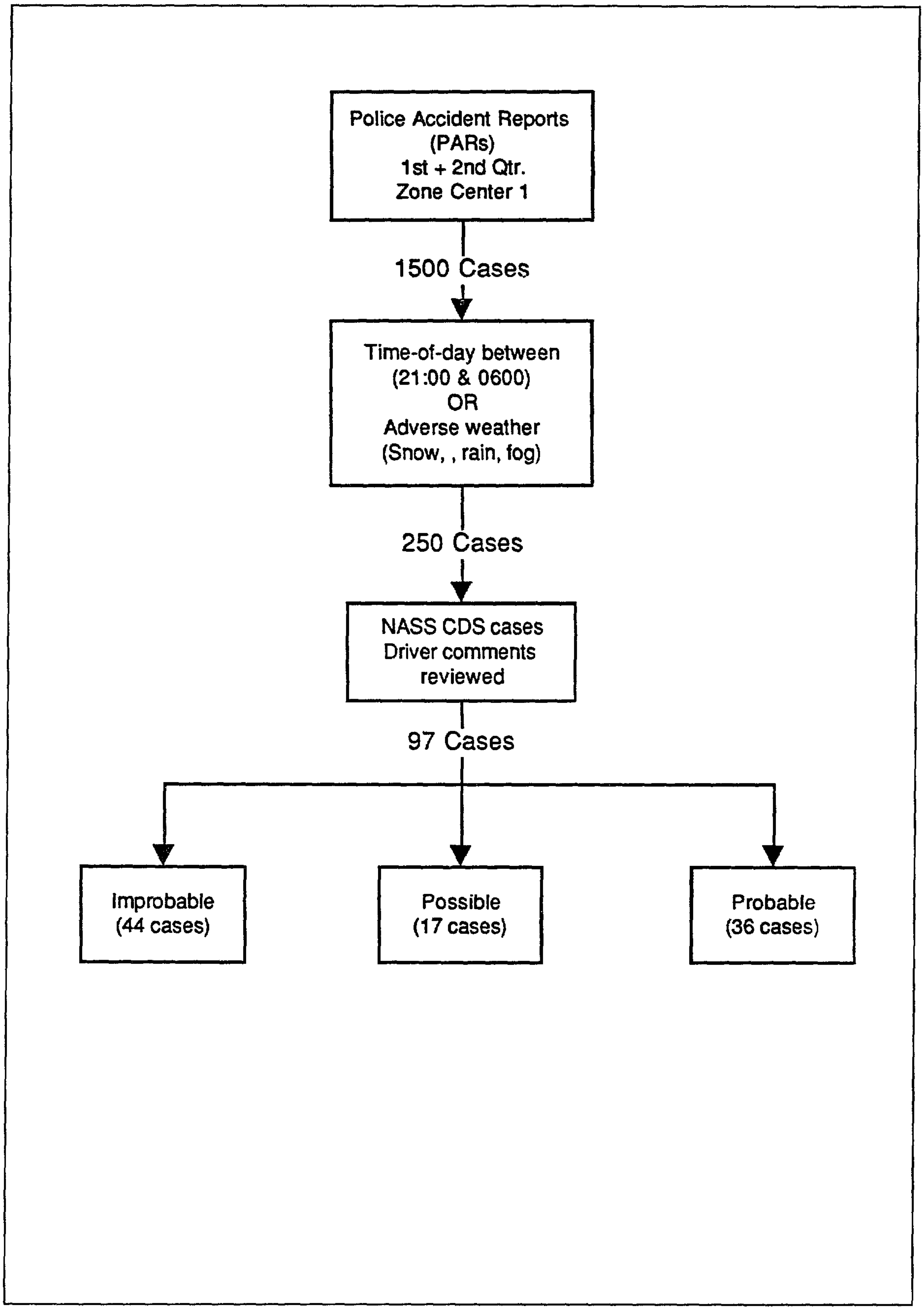


Figure 3-1. Reduced Visibility Data Set Sampling Criteria

Table 3-1
Classification Rules For Reduced Visibility Cases

Classification	Environment	Driver	Other Causes
Probable Reduced Visibility Crash	Night OR Adverse	States Inability to Observe OR Insufficient Time To Respond	No Fatigue, No DUI, etc.
Possible Reduced Visibility Crash	Night OR Adverse	Does NOT State Inability to Observe OR Insufficient Time To Respond	No Fatigue, No DUI, etc.
Improbable Reduced Visibility Crash	Night OR Adverse		Yes Fatigue, OR Yes DUI, OR Similar Factors

Table 3-2 shows the frequency and weighted percentage of crashes by crash type for each case classification, Roadway departures were the single largest category of reduced visibility crash type for both probable cases (29.5 percent) and possible cases (45 percent). The next largest categories of reduced visibility crashes include rear-end, sideswipe/angle, and intersection crashes (both turning crashes and straight crossing paths crashes).

To further characterize the reduced visibility crashes, the probable and possible case categories were combined as reduced visibility cases (see Table 3-3). Each of the cases were analyzed by whether or not a driver attempted an avoidance maneuver prior to impact. This was done by examination of the pre-crash variable GV14 from the CDS General Vehicle Form (see Appendix B and C). The results of this analysis are shown in the right two columns of Table 3-3. Overall, about 62 percent of such cases did not involve an attempted avoidance maneuver. In these cases, the driver either did not realize that a collision was impending or did not have enough time to respond once it was realized.

3.3 DISCUSSION

The crash types listed in Table 3-3 suggest two major categories of reduced visibility crash problems. One category, which includes vehicle departure from the roadway, involves inability to see lane delineation markings and roadway alignment. A second category of reduced visibility problems, which includes striking an obstacle in the road, head-on collisions caused by improper passing, rear-end collisions, and turns across path involves

Table 3-2
Percentage of Accidents by Crash Type and Case Classification

Crash Type	Probable Cases	Weighted Percent	Possible Cases	Weighted Percent	Improbable Cases	Weighted Percent	Total Cases	Total Sample Weighted Percent
Roadway Departure								
Right, Drive-Off Road	3	5.1%	1	1.0%	6	10.3%	10	6.7%
Right, Control/Traction Loss	3	10.3%	4	23.0%	1	3.8%	8	9.6%
Left, Drive-Off Road	4	10.1%	2	4.0%	2	3.1%	8	6.2%
Left, Control/Traction Loss	2	4.0%	2	17.0%	5	9.2%	9	6.8%
Forward Impact-Stationary Object	1	2.4%	0	0.0%	1	1.1%	2	1.2%
Rear-End	6	18.4%	2	1.9%	4	12.4%	12	14.1%
Head-On, Lateral Move	2	5.7%	0	0.0%	2	5.8%	4	4.8%
Sideswipe/Angle	2	2.7%	2	19.0%	3	6.2%	7	6.4%
Turn Into Path								
Turn Into Same Direction	1	1.1%	0	0.00%	1	3.8%	2	2.2%
Turn Into Opposite Direction	4	11.8%	1	1.0%	1	1.1%	6	5.6%
Turn Across Path								
Initial Opposite Directions	4	16.1%	1	16.0%	10	21.0%	15	18.3%
Intersection Crash								
Straight Crossing Path	2	6.1%	2	17.0%	7	18.5%	11	13.8%
Other (U-Turn)	2	6.1%	0	0.0%	0	0.0%	2	2.4%
No Impact	0	0.0%	0	0.0%	1	3.8%	1	1.8%
TOTAL	36	99.9%	17	99.9%	44	100.1%	97	99.9%

Notes: See Appendix A for weighting scheme

Table 3-3
Frequency of Combined Reduced Visibility Cases by Crash Type and Attempted Avoidance Maneuver, Probable Plus Possible Cases

	Attempted Avoidance Maneuver?					
	Yes		No		Unknown	
Crash Type	Cases	Percent	Cases	Percent	Cases	Percent
Roadway Departure						
Left, Control/Traction Loss	1	1.3(2.4)	0	0.0(0.0)	3	3.9
Left, Drive-Off Road	2	4.9(6.1)	2	2.7(4.5)	2	1.9
Right, Control/Traction Loss	5	12.5(15.2)	2	1.9(3.2)	0	0.0
Right, Drive-Off Road	1	1.3(2.1)	3	2.4(3.9)	0	0.0
Forward Impact-Stationary Object	0	0.0(0.0)	0	0.0(0.0)	1	1.3
Head-On, Lateral Move	0	0.0(0.0)	1	3.6(4.0)	1	0.5
Rear-End						
Forward Vehicle Moving	2	4.1(4.8)	3	6.28(8.30)	2	4.9
Forward Vehicle Slower	0	0.0(0.0)	0	0.0(0.00)	1	0.5
Sideswipe/Angle	1	1.3(2.1)	1	3.60(4.0)	2	1.9
Turn Across Path Initial Opposite Direction	1	3.56(4.01)	3	10.68(12.02)	1	1.34
Turn Into Path						
Turn Into Opposite Direction	1	0.5(0.7)	3	5.4(6.9)	1	3.6
Turn Into Same Direction	0	0.0(0.0)	1	0.5(0.7)	0	0.0
Intersection Crash-Straight Crossing Path	0	0.0(0.0)	4	8.9(10.9)	0	0.0
Other (U-Turn)	0	0.0(0.0)	1	3.6(4.0)	1	1.3
Total	14	29.5(37.4)	24	49.5(62.4)	15	21.1

Notes: (1) See Appendix A for weighting scheme.
(2) Percentages in parentheses are those obtained under the assumption that unknowns are distributed similarly to knowns.

inability to see objects ahead. Neither category includes crashes that occur as the result of collision-avoidance maneuvers.

Roadway departures are events in which lateral control of the vehicle is not maintained within the specified boundaries of the roadway. This category includes those cases where the vehicle departed from the road either because the driver failed to detect roadway edges or because the driver failed to negotiate a curve – which could happen because of the driver's inability to detect the turn in time or from underestimating the

Table 3-4
Roadway Departure Characteristics

Direction	Type of Departure	Avoidance Maneuver	Comments	Curve?
Right	Drive-Off Road	None	Approach curve too fast	Yes
Right	Drive-Off Road	None	Failed to negotiate curve	Yes
Right	Drive-Off Road	None	Left right side of road	
Right	Drive-Off Road	Braking: Lock-up	Blinded by headlights	
Left	Drive-Off Road	Unknown	Failed to negotiate curve (R)	Yes
Left	Drive-Off Road	Unknown	Failed to negotiate curve (R)	Yes
Left	Drive-Off Road	Braking: Lock-up	Blinded by high-beam headlights	
Left	Drive-Off Road	None	Drove left of center on left curve	Yes
Left	Drive-Off Road	Braking: Steering Right	Lost control OR failed to detect right curve	Yes
Left	Drive-Off Road	None	Ran off right side of road	
Right	Control/Traction Loss	None	Exit right curve, hit trees	Yes
Right	Control/Traction Loss	None	Ran off right side, straight road	
Right	Control/Traction Loss	Steering: Left	Too fast for conditions	
Right	Control/Traction Loss	Braking: Steering Left	Exit left curve on right side, excessive speed	Yes
Right	Control/Traction Loss	Braking: Steering Left	Loss of control on right curve	Yes
Right	Control/Traction Loss	Breaking: Steering Left	Left road, hit tree	
Right	Control/Traction Loss	Braking: Steering Right	Exit sharp curve, too much speed	Yes
Left	Control/Traction Loss	Unknown	Poor visibility due to snow	
Left	Control/Traction Loss	Unknown	Lost control/hydroplane	
Left	Control/Traction Loss	Unknown	Ran off right side of left curve	
Left	Control/Traction Loss	Braking: Lock-up	Failed to observe turn in road	Yes

severity of the curve. Table 3-4 lists the roadside departure cases found in the CDS sample. It includes the direction the SV departed the road, the type of departure, the avoidance maneuver used by the driver, factors that contributed to the departure, and whether the roadway curved. Roadway departure at a curve occurred in 11 out of 21 cases and 5 of those 11 cases occurred with associated loss of control or poor traction. In general, then, roadway departures in reduced visibility conditions are often associated with a lack of information about lane edge markings and roadway alignment ahead. Inability to read "curve ahead" warning signs may also play a role. In some cases, a loss of traction due to poor road conditions (e.g., gravel, snow, ice) can also contribute to departing the roadway.

Reduced visibility conditions degrade contrast, motion perspective, or motion parallax, and occlusion/disocclusion information, which reduces the driver's ability to maintain lateral control as a function of roadway edge lines. It degrades detection of obstacles as well. There may be cases when a driver changes lanes or passes assuming it is safe to do so. If visual information is degraded because of fog or rain or low-ambient lighting, then a driver's ability to perceive looming objects is less than optimal. A driver may not perceive an approaching vehicle and may assume that it is safe to change lanes or pass or turn left at an intersection or these maneuvers may be in progress when a driver perceives an oncoming vehicle without sufficient time to respond. Examples of this phenomenon are described by Lee (1992); road signs and other objects are said to "pop out" at the last minute under foggy conditions. Lee also points out that even if some sight distance is available, a driver may perceive an object to be farther away than it actually is because of the reduced visual detail available to detect and identify an object. Clearly, the problem of object detection in reduced visibility conditions is inherent in pedestrian mishaps, animal strikes, and rear-end crashes as well. Regarding rear-end crashes in reduced visibility conditions, Rockwell (1992) provides some interesting perspectives. He points to evidence that drivers adopt strategies in order to reduce the demands associated with lateral control by finding and following a lead vehicle under reduced visibility conditions. As Rockwell mentions, adopting this behavior places the shortcomings of the lead vehicle (degraded sight distance, decreased awareness of environment and other vehicles, etc.), on the following vehicle and may actually increase the risk of a rear-end crash.

It is clear that fog and rain reduce the ability of an observer to perceive contrast and visual angle attributes of an object or visual scene. Hence, the ability to detect lane edge markings, roadway alignment, and curves based on purely fovea1 cues is degraded. In addition to degraded foveal aspects of the visual scene, the more peripheral or ambient visual characteristics are likely to be degraded as well. If ambient sources of visual information (e.g., motion perspective or motion parallax) are lacking because of reduced visibility, then a driver may not realize that the approach speed when coming upon a curve is excessive. If this is the case, the potential for poor judgments with regard to safe travel speed, distance to a curve, and closure rates is probably increased.

Perhaps some drivers are not aware of the degraded ambient visual condition. Drivers typically exhibit highly varied speeds in fog (Rockwell, 1992) and under nighttime driving conditions (Liebowitz, 1988). It is possible that a lack of ambient stimulation could suggest to drivers that their travel speed is slower than it actually is. This may account for drivers that underestimate actual speed under fog conditions (Rockwell, 1992).

4. IVHS CRASH AVOIDANCE CONCEPTS FOR REDUCED VISIBILITY CRASHES

4.11 INTRODUCTION

The previous section suggested how reduced visibility might affect the availability of visual information needed to safely control a vehicle and avoid hazards. This section suggests some countermeasures that might be used to compensate for reductions in visual information availability. Table 4-l presents an overview of these countermeasures. The discussion that follows is based on this table.

4.2 IN-VEHICLE CRASH WARNING SYSTEMS

Reduced visibility is a crash circumstance that may be associated with a variety of crash types such as rear-end, roadway departure, head-on, and intersection crashes, among others. This suggests that in-vehicle crash warning systems directed toward alleviating these various crashes could be of benefit for reduced visibility conditions as well. For rear-end crash avoidance, candidate systems include forward-looking radar or laser systems that present an in-vehicle warning if the driver is approaching a lead vehicle too closely. For roadway departure/drift-out-of-lane crash avoidance, laser-based lane sensors and machine vision systems could present a warning to the driver when the vehicle is leaving the lane. For intersection crash avoidance, vehicle-to-roadway communication or vehicle-to-vehicle communication systems may be appropriate. See Najm (1994b) for a review of these and other IVHS crash avoidance technologies. For the application of various crash avoidance system concepts to specific crash types, see Fancher, Kostyniuk, Massie, Ervin, Gilbert, Reiley, Mink, Bogard, and Zoratti (1994); Knipling, Mironer, Hendricks, Tijerina, Everson, Allen, and Wilson (1993); Tijerina, Hendricks, Pierowicz, Everson, and Kiger (1993); and Chovan, Tijerina, Alexander, and Hendricks (1993).

The driver interface to such crash warning systems may be auditory, visual, or tactile in nature. Visual displays typically consist of alphanumerics, symbols, colored lights, or icons (e.g., outline of a vehicle). Auditory displays are typically beeps that may be coded by pitch, intensity, duration, or wave form to convey information to the driver. Speech warnings are also a possibility (COMSIS, 1993). Tactile displays may provide warnings or cautions to the driver by forces provided from the system to the driver via the steering wheel or pedals. Note that none of these displays convey optical information about the driving situation. In this way, these systems do not help the driver "see" the hazard. Nevertheless, they may be useful for reduced visibility crash avoidance. Many of the reports referenced in the preceding paragraphs discuss the many issues that surround the development of crash warning systems. The issues range from sensor performance to algorithm development to driver interaction with and reaction to the warning system.

Table 4-l. Possible Countermeasures

Category	Examples	General Characteristics
In-Vehicle Warning Systems	Headway detection systems, near object detection systems, lane position monitors.	Require sensors, processors, and driver display (but NOT an image of road scene). Provide overt alerts or warnings.
Roadway Information Systems	Variable Message Signs (VMS); Rumble Strips.	Do not require electronic sensors, in-vehicle processors, or displays. VMS provides information; rumble strips provide overt warning.
Direct Vision Enhancement Systems (DVES)	Improved Taillights; Ultraviolet Headlights; Polarized Headlights.	Do not require a detector, processor, or display. Driver's direct perception is enhanced. Do not provide overt warning.
imaging Vision Enhancement Systems (IVES)	Charge-Coupled Device (CCD) Cameras; Passive Far-infrared imaging; Active Millimeter-Wave Radar Imaging; Passive Millimeter-wave Imaging.	Do require sensor or detector, illumination (for active systems), processor, and in-vehicle video display or head-up display (HUD) that presents an image of the road scene. Do not provide overt warning signals.

4.3 ROADWAY INFORMATION SYSTEMS

Reduced visibility crashes might be alleviated by roadway information systems. Traditionally, road signs, traffic signals, and pavement markings have been used to provide the driver with information about appropriate travel velocity, the need to brake, potential obstacles to watch for, and changes in roadway alignment. Within the IVHS umbrella, Variable Message Signs (VMS) might alert the driver of poor visibility conditions ahead and suggest appropriate reduced travel speeds or alternate routes. Schwab (1992) describes some data that show that, although drivers are not effective judges of the severity of visibility conditions, they will slow down in response to advisory messages. In one study, Schwab found that, although drivers did not slow down as much as they should have, they did begin reducing speed sooner than they did without the VMS. However, to be effective, the VMS information must be accurate. If not, drivers will tend to ignore the VMS information later when it is (again) accurate. In fact, Schwab suggests that drivers need repeated exposure to accurate signage (eight to ten exposures) to overcome the loss of trust incurred by a single exposure to inaccurate or dated information. In addition to providing accurate information early enough for the driver to make a change in driving, the VMS must be readily visible to the driver, and must be properly maintained. In addition, in-vehicle signing (De Vaulx, 1991) is an alternate to VMS that may compensate for poor visibility of the VMS and may enhance driver awareness of the message. In-vehicle signing is being incorporated into the TravelAid operational test to convey inclement weather information to drivers (Federal Highway Administration, 1994). VMS and in-vehicle signing do not provide the driver with enhanced visibility of the road scene ahead, but they may prevent crashes with obstacles by the kind of information they convey.

Rumble strips may be another example of a roadway information system that is particularly useful for avoiding roadway departures in reduced visibility conditions. Wood (1994) presented promising results of using shoulder rumble strips for alerting “drifting’: drivers. Installation of shoulder rumble strips along selected segments of the Pennsylvania Turnpike resulted in a 70 percent reduction in roadway departure crashes. While primarily intended to alert the drowsy driver, it should also be of benefit for drivers who cannot see lane markings due to fog, snow, rain, or other obscurants.

4.4 DIRECT VISION ENHANCEMENT SYSTEMS

Direct vision enhancement increases the type or amount of information normally available to the driver from sources outside of the vehicle. Examples of direct vision enhancement are taillight redesigns and ultraviolet high-beam headlights. Rockwell (1992) describes an example of a taillight redesign that involved supplementing the external lights on the lead vehicle so as to provide the driver of the following vehicle-with additional information. Although this approach apparently has never been formally evaluated, it is, nonetheless, an interesting approach. Rockwell’s team at Ohio State University constructed a taillight consisting of a red light with three boxes. At long distances, the red light appeared as a single box. When the distance to the vehicle decreased, two boxes could be seen. If the distance was very tight, three boxes were seen. In effect, the following driver could gauge the distance between the two vehicles on the basis of the appearance of the taillight. Individual differences in visual acuity would affect the effectiveness of such a device. Another potential limitation with this approach stems from the possibility that it could backfire under reduced visibility conditions in that the following driver could be misled by a false perception of distance. “Smart” taillights might change in brightness in response to reduced visibility conditions.

Glare from oncoming vehicle headlights at night reduces visual performance and so is a source of reduced visibility. Another form of direct vision enhancement that is intended to reduce glare and increase seeing distance is polarized headlighting (Johansson and Rumar, 1968; Perel, 1994). The system consists of a polarized filter over each headlight and a polarized filter (the analyzer) through which the driver views the oncoming traffic. Since the polarization axis of the opposing traffic headlights is 90 degrees from the analyzer, the headlight intensity is greatly reduced when viewed through the analyzer. An analyzer may also be placed on rear view mirrors to reduce glare from following vehicles. While Perel (1994) notes a number of technical challenges to be solved in bringing polarized headlighting into common use (including reduced light transmittance through the polarized filters and the need for all vehicles to be equipped with both filters and analyzers), this may also be a useful addition to IVHS technologies for reduced visibility crash avoidance. It may be particularly useful for older drivers who are especially susceptible to disability glare.

Ultraviolet high-beam headlights, used in addition to normal low-beam headlights, can increase the visibility range at night up to 200 meters (656 feet), yet do not cause blinding glare to oncoming traffic (Najm, 1994; Fast & Ricksand, 1994). To be effective, however, fluorescent pigments must be embedded in those objects (clothing, road signs, lane markings, vehicles, etc.) to be made visible to the driver. In spite of this limitation, UV headlights are a potentially valuable approach since they are not disrupted by fog, mist, and small amounts of snow. Furthermore, detergent residue on clothing generally provides sufficient fluorescence to make pedestrians much more conspicuous at night than they would be with standard lamps. A potentially adverse consequence might be that if fluorescent objects show up well this might prompt drivers to drive faster even though nonfluorescent objects are not more visible, thus increasing overall crash risk,

Direct vision enhancement as a countermeasure category, is of special interest as a reduced visibility support because such systems enhance the natural functioning of the human visual system. No special displays are required that can serve to distract the driver from the main task of monitoring the movement of the vehicle along the road. Nor must the driver learn how to interpret the information provided by a display. For these reasons, direct vision enhancement should be considered an important potential aid for reduced visibility driving.

4.5 IMAGING VISION ENHANCEMENT SYSTEMS

Imaging vision enhancement systems (IVES) use sensors that can penetrate the darkness or atmospheric obscurants to present the driver with an image of the road scene superior to that available to the naked eye. The driver would be presented with a visual representation of the road scenario with sufficient range ahead that crash avoidance is feasible, perhaps with a recommended travel speed (Fancher et al., 1994). As Najm (1994a, 1994b) points out, such a system requires sensors (e.g., infrared, active or passive millimeter-wave radar imaging, charge-coupled device (CCD sensors), illuminator (for active systems), processor, and driver display. Imaging VES do not provide overt warning of obstacles (though there may be an excessive speed warning). Instead, these systems provide (in principle) optical information that the driver needs for vehicle control and object detection. Imaging is frequently presented as a concept for reduced visibility crash avoidance (Fancher et al., 1994; Kippola and Stando, 1994; McCosh, 1993).

Discussions of imaging sensor technologies are provided by Najm (1994a) and Hahn (1994). At present, all imaging sensor technologies have limitations. Passive far infrared sensing is commonly referred to for automotive applications. It operates by sensing the thermal signature of objects that are warmer than their backgrounds (e.g., cars, pedestrians, animals). Hahn (1994) reports on studies conducted at BMW in Europe and points out that in rain or snow, the infrared spectral range is not useful due to the low contrasts coming from wet object surfaces. In haze or fog, Hahn reports that infrared visibility is in most cases less than or equal to the visible spectral range. At night, far infrared sensing may be useful provided that it can be made available with sufficient range, resolution, and price.

Active millimeter-wave radar imaging is currently under investigation by Ford Motor Company (Hughes, 1993; Kippola and Stando, 1994). While the image presented in a simulated head-up display (HUD) shows highlighted lane markings and icons of vehicles in the fog ahead, there are problems to be overcome. For example, such a system will not work without treating the pavement markings (and, presumably, other signs) with a reflective material. Najm (1994a) also points out that such sensor technology, in general, cannot provide the same level of image resolution as that available in the visible or infrared range. These and other technical limitations must be solved before such a system will be viable for the automobile and truck.

Charge-coupled devices (CCD) are undergoing a variety of research and development efforts. CCD cameras are sensitive from the ultraviolet, visible, and near infrared spectral range. Under low light conditions, an image intensifier is used which, unfortunately, makes the cameras prone to streaking and blooming from bright sources (e.g., headlights from oncoming cars or trucks). Najm (1994a) points out that active illumination enhances CCD performance only to the extent to which there is good contrast transmission through the atmosphere between the object to be sensed and the camera. Target contrast is thereby reduced in the presence of atmospheric obscurants. Taken together, there is no clearly superior sensor technology for imaging vision enhancement. Indeed, Hahn (1994) suggests that an imaging VES in the short-term is unlikely.

VES image presentation may be provided to the driver either as an in-vehicle cathode ray tube (CRT) display or as a head-up display (McCosh, 1993). Like other high-technology devices finding their way into cars and trucks, there is concern that the in-vehicle CRT may increase the driver’s workload (Tijerina, Kantowitz, Kiger, and Rockwell, 1994). Concerns include increased visual allocation to the CRT rather than the road scene and disruption of driver-vehicle performance while looking at the CRT. The latter has already been reported by Mutschler (1992) who found, in addition, that for many driving maneuvers (e.g., lane changes), the visual range provided by the monitor is far from adequate. It is likely that a CRT for imaging VES will demand much more of the driver’s visual attention than mirrors, instrument panel displays, or other electronic displays. Coupled with the limited space available in instrument panels and the potential for miniaturization that will restrict display observation considerably, many researchers are looking at the second display alternative, the head-up display (HUD).

A brief review of several studies of HUD applications for vision enhancement will serve to introduce the human factors issues involved. Nilsson (1993) described work by Nilsson and Alm (199 1) who investigated vision enhancement in a driving simulator by simulating driving in clear conditions, fog, and fog with a simulated vision enhancement system that consisted of a monitor positioned on the hood near the windshield (i.e., simulating a HUD). On the monitor a clear picture of the road and its environment was presented to the driver. Drivers in the simulator chose higher travel speeds with the HUD than without the vision aid (Nilsson and Alm, 1991, reported in Hahn, 1994). Enhanced visibility benefits could be negated by higher speeds, especially if reduced visibility due to weather is accompanied by poorer traction or if higher speeds are not expected by other drivers sharing the roadway.

Ward, Stapleton, and Parkes (1994) reported on a field study of a contact-analogue HUD providing infrared images directly on the windshield superimposed on the actual objects in the road scene. Compared to no HUD, drivers drove more slowly and reported higher subjective workload than when using the prototype HUD. Tijerina, Kantowitz, Kiger, and Rockwell (1994) point out that speed reduction is a common technique drivers use to manage high workload, so these results are consistent with other human factors data. From comments made by Ward in an oral presentation of this paper and a video tape presentation of the contact-analogue HUD, it was clear that the display was quite difficult to drive with due to the time delay in superimposing the infrared image with the real object and in the ghostly appearance of the infrared images. Given that Nilsson and Alm (1991) used an idealized (simulated) HUD, the results of Ward et al. (1994) are not inconsistent. What is clear is that drivers will have difficulty in getting accustomed to the unnatural HUD imagery that is likely to be feasible (at least with infrared sensors) in the near term.

HUDs are supposed to enhance safety because the driver does not have to take eyes off the road. However, due to packaging constraints only a portion of the road scene ahead will be subject to enhancement; this is called the HUD “eye box.” The scene outside the HUD will remain without enhancement. It is possible that the benefits of HUD vision enhancement will be offset by a reduced rate of detection of events in the periphery. Bossi, Ward, and Parkes (1994) conducted a simulator study of this and found significant impairment of peripheral target detection and identification performance under conditions intended to simulate night. These results need to be replicated using other methods since it was a simulator study rather than real-world driving, the targets were symbols presented in various locations rather than actual objects, and the dependent measure was the driver’s response time to activate the high-beam stalk. However, it appears that the HUD for vision enhancement may capture driver visual attention to objects outside the eye box.

As these studies of HUD-display VES show, there are several human factors issues that must be addressed by further research. Hahn (1994) succinctly points out several of these issues. As indicated in Ward et al. (1994), mismatch between the image and the direct view can increase subjective workload and possible misinterpretation of visual information. Road vibration of the sensors and/or displays may aggravate this problem. The HUD imagery may reduce the contrast of the directly perceived scene by 10 to 20 percent, with an associated reduction in object detection distance. Hahn points out that even with perfect superposition of images and their associated objects, images can look very different. Thus, the ability of the driver to learn to apprehend such imagery, and the training required to develop this ability, are also key research questions. The limited field of view of sensors compared to the driver's visual field (as well as the eye box) suggests that the HUD may provide a tunnel-vision view of the road scene. The impact of such technology to affect driver behaviors (e.g., visual allocation) and driver-vehicle performance (e.g., driving speed, lane-keeping performance) must also be assessed.

5. MECHANISMS OF REDUCED VISIBILITY

5.1 INTRODUCTION

This section addresses how reduced visibility from obscurants and ambient lighting affects sight distance. Obscurants and ambient illumination contribute to reduced visibility by reducing inherent contrast and increasing threshold contrast; this, in turn, affects the sight distance of different target sizes. The impact of reduced visibility sight distance on stopping distance is examined below. Similar analyses for steering sight distance could be developed, but are likely to be more complex and so are omitted here. However, see Allen and McRuer (1977) for an analysis of the effects of sight distance on steering performance.

Formal models for the effects of obscurants (Koschmeider's Law) and ambient illumination (Blackwell's equations) are available and are discussed here, but a database for and the application of these models to the driving situation has not been explicitly established. Furthermore, no model was found that combines both obscurant and illumination effects.

Reduced visibility also may reduce the probability of detection, given that the driver's vigilance varies and the driver scans the road scene for objects of importance (e.g., obstacles, pavement markings, road signs, pedestrians).

5.2 OBSCURANTS AND CONTRAST REDUCTION

Particles suspended in the atmosphere scatter and absorb light so that an object becomes harder to see and distinguish. Fog, smoke, sleet, rain, etc., all behave as obscurants that reduce the visibility range, and thus pose a significant hazard for the driving task. Koschmeider (1924) provides a theory of visual range that is used to address the effect of obscurants on sight distance.

Most of us are familiar with the visual cue of aerial perspective that is demonstrated by the apparent lightening in tone of more distant objects, such as a mountain range, when viewed from a remote locality. This cue is caused by the scattering (mainly) and absorption of light by the atmosphere between the viewer and the object, which creates an increase in luminance with distance so that, eventually the object's luminance approaches that of the horizon and the object "disappears." In the driving task, this is analogous to a change in the apparent luminance of a visual target and its background due to light scattering and absorption caused by any of the above-mentioned obscurants.

Conditions that reduce the ability to perceive differences in luminance between an obstacle or lane markings and the surrounding environment degrade obstacle detection and detection of lane markings. Without a difference in target and background luminance, there will be no detection regardless of target size. The relationship between target and background luminance is the contrast, C, and is defined as:

$$C = \frac{B_T - B_B}{B_B} \tag{1}$$

where

B_T	=	target luminance, foot-lamberts
B_B	=	background luminance, foot-lamberts

In the case of stray light from a glare source or backscatter brightness, this veiling luminance alters the target and background brightness and the contrast becomes:

$$C = \frac{B_T - B_B}{B_B + B_V} \tag{2}$$

where

B_V	=	veiling luminance caused by glare sources or backscatter brightness, foot-lamberts

The effect of uniform atmospheric distribution (e.g., fog, haze) under daylight conditions upon contrast reduction along a horizontal field of sight is represented by Koschmeider's Law and is presented by Middleton (1952) as:

$$C_D = C_0 e^{-\sigma D} \tag{3}$$

where

C_D	=	apparent contrast to the observer at distance D
C_0	=	inherent contrast between target and background at $D=0$
σ	=	attenuation or extinction coefficient of the intervening medium, 1/ft
D	=	distance between the target and the observer, ft

If the apparent contrast exceeds threshold, then the target will be detected. Blackwell has done extensive research in the area of threshold contrast, which is summarized in CIE 19/2.1 (1981). The results of his research are represented by threshold contrast curves as in Figure 5-1. These curves plot threshold contrast as a function of background luminance, target size, and exposure times. Frenk, et al. (1972) discuss the limits of these data, when applied to the automobile, such as the assumptions of a uniform brightness background, adaptation, detection time, and expectations of the observer.

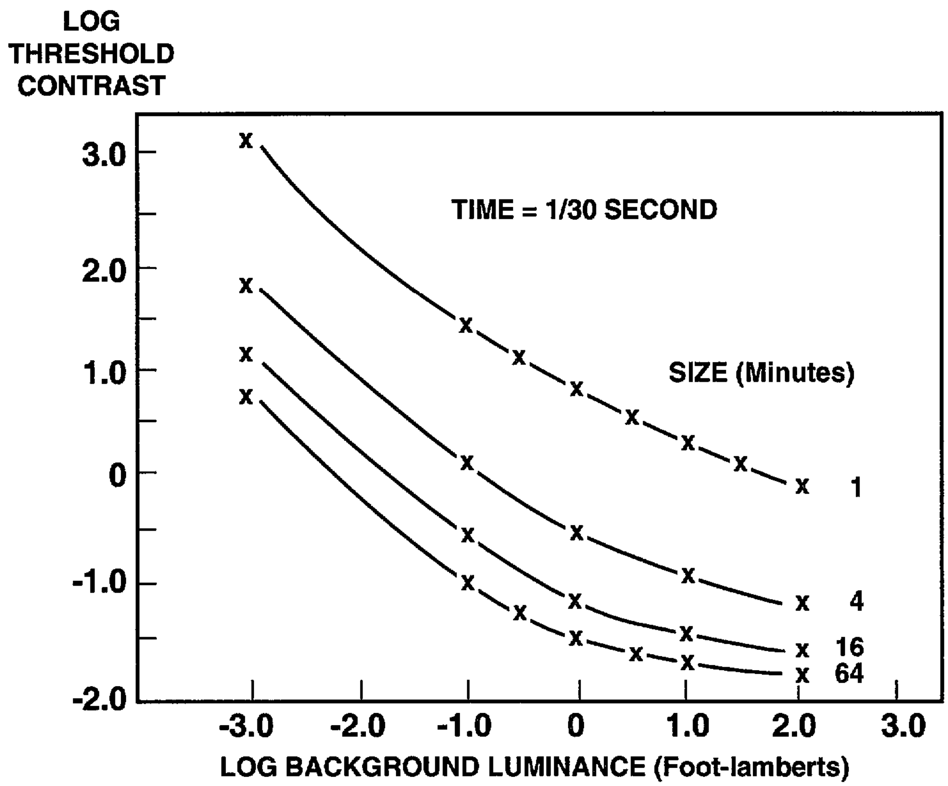


Figure 5-1. Log Threshold Contrast as a Function of Background Luminance for Different Size Targets presented for 1/30 of a second (Source: Blackwell, 1954.)

From Allen and McRuer (1977), Figure 5-2 indicates Koschmeider's Law for a given $C_0 = 2.0$ and $\sigma = .023$ marked by the circled A. Allen and McRuer also include an extrapolation to approximate the effects of glare and backscatter marked by the circled B. Such veiling luminances cause contrast to attenuate more rapidly with range or sight distance. Visibility range is determined by finding the range at which the object contrast falls below the observer's threshold contrast. For example, consider the contrast thresholds for a 4-in wide road marking stripe 15 ft in length depicted in the figure. If apparent contrast is above threshold contrast, then detection of the road marking occurs; otherwise detection does not occur. Since threshold contrast is a function of visual size, the threshold contrast line slopes upward and to the right with increasing range. Given the conditions depicted, at 200 ft, the log threshold contrast for the 15 ft road marking is about .06 yet the apparent log contrast is below .02. Therefore, the driver would not be able to see the road marking delineation the lane 200 ft ahead. Based on the intersections between threshold and apparent contrast curves, the driver would only be able to see the roadway marking at about 170 ft ahead and with increased contrast attenuation at night due to backscatter and glare effects, only about 145 ft ahead.

Table 5- 1 provides descriptions of visibility conditions and associated meteorological optical ranges, These are ranges at which a large black object can be seen against the horizon sky with a contrast of 0.05 (Kaufman, 1981). Clearly, this does not represent all the various driving conditions in which drivers might find themselves. However, the table provides at least some phenomenological reference points for the reader of sight distances under different atmospheric conditions. For example, a weather advisory that mentions "dense fog" may involve visibility ranges of around 330 ft, possibly less.

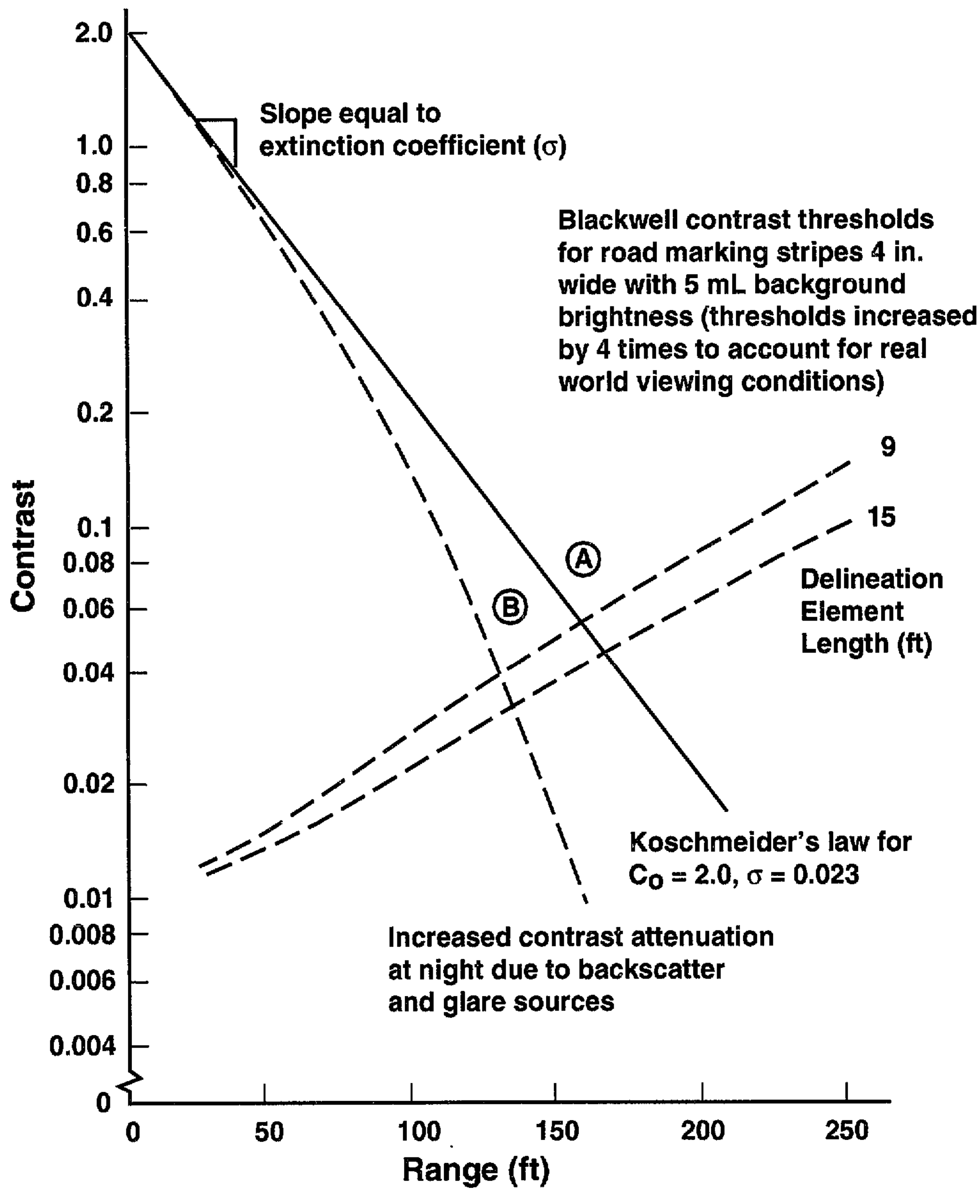


Figure 5-2. Delineation Visibility Performance Under Adverse Visibility Conditions (Source: Allen & McRuer, 1977)

Table 5-l
Meteorological Optical Ranges for Various Visibility Conditions
(Source: Kaufman, 1981)

Visibility Description	Meteorological Optical Range, R_o (miles)
Exceptionally clear	30+
Very clear	30
Clear	10
Light Haze	5
Haze	2
Thin fog	1
Light fog	I/2 (2,640 ft)
Moderate fog	I/4 (1,320 ft)
Thick fog	I/8 (660 ft)
Dense fog	1 /16 (330 ft)
Very dense fog	100 ft
Exceptionally dense fon	50 ft

5.3 AMBIENT ILLUMINATION AND CONTRAST REDUCTION

Koth, McCunney, Duerk, Janoff, and Freedman (1978) presented Visibility Index (VI) and Visibility Index/Fog (VI/FOG) models to capture the effects of ambient illumination and fog on visibility. The basic equation used is the Visibility Index:

$$VI = C \times RCS(B_B) \times DGF \qquad (4)$$

where

VI	=	Visibility Index, given as apparent contrast
ICI	=	Absolute value of inherent contrast of target and its background
$RCS(B_B)$	=	Relative contrast sensitivity of an observer adapted to background luminance B_B, given as a proportion
DGF	=	Disability Glare Factor, given as a proportion

The VI model provides an apparent contrast based on inherent contrast times: a) a multiplier, RCS(B_B), that takes into account the sensitivity of the driver adapted to some background luminance level, and b) a second multiplier, DGF, that takes into account loss in visual performance due to veiling glare. This formulation was modeled after the work of Blackwell,

The VI/FOG model used the same basic formula as the VI model. Only the fundamental luminances (B_T, B,, and B,) were changed to model the fog visibility effects. These luminances were attenuated by the attenuation coefficient e^{-0} according to integration formulas presented in Koth et al. (1978). These formulas take into account various distances and angular separations between driver, target, subject vehicle headlamp, and glare sources, as well as fog characteristics, tail lamp and headlamp intensity, and target reflectance. A validation study of VI/FOG was conducted by taking various luminance measurements in dense nighttime fog. Results indicated some differences between measured and predicted values for the luminances, RCS, DGF, and VI values. These differences may have been due to subtle environmental effects (e.g., full moon present), measurement errors associated with the photometers and lenses available at the time, or possibly to algorithms in the VI/FOG computer program producing the calculated values. This modeling effort nonetheless provided an important integration of key aspects of reduced visibility analysis. The assessment of fog lamps and rear light systems available at that time indicated that the greatest potential for visibility enhancement was in improved rear lamps, and that opportunities for daytime visibility enhancement (with lamps) in fog were limited.

Since the VI and VI/FOG models were developed, there have been refinements in incorporating the work of Blackwell for visibility assessment, particularly by taking into account driver age differences in contrast sensitivity and disability glare susceptibility. Perhaps the most recent model to incorporate these refinements into the Blackwell system is PCDETECT by Farber and Matle (1989). It is noteworthy, however, that PCDETECT does not incorporate formulas to address atmospheric attenuation.

Generally, threshold contrast increases with smaller targets and with lower levels of illumination, as seen in Figure 5- 1. The effect of luminance on contrast reduction has been implemented in a computer sight distance program called PCDETECT (Farber and Matle) (1989). This program is specifically designed as a headlamp-seeing distance model that uses contrast threshold data from Blackwell's research. Detection of lane lines, pavement markings, traffic signs, and pedestrians are some of the targets with which PCDETECT deals. PCDETECT uses approximately 40 parameters to iteratively compute a contrast for a target of a given visual size, compare it to the threshold contrast, and determine a visual range or seeing distance.

PCDETECT parameters include background luminance, driver age, glare, target reflectance, headlamp type, and road geometry. For a specific application, PCDETECT permits data to be input for these parameters in order to compute a meaningful seeing sight distance. Although PCDETECT was developed as a headlamp model, daylight conditions may be simulated by inputting the ambient level to some typical daytime value, such as 1,000 foot-lamberts. This effectively reduces the contribution from headlamp illumination to a negligible value. Screen dumps that illustrate a daylight seeing distance condition to see a pedestrian and the range of parameters are given in Figure 5-3. Figure 5-4, from Farber and Matle (1989), shows the sensitivity of seeing distances (distances to see a lOO-ft, 4-in wide pavement line) to glare, age, and percentile contrast sensitivity. Increasing age corresponded to a decrease in sight distance in a nonlinear manner with the rate of decrease increasing with age.

Fast and Ricksand (1994) implemented the algorithms used by PCDETECT to evaluate vision enhancement with UV headlights versus modifications for European low beams. UV light is invisible, but is emitted when aimed at a fluorescent surface visible light. Detergents that contain optical brighteners increase the fluorescence of several materials. Figure 5-5 illustrates the results of a simulation using PCDETECT algorithms. The vision enhancement provided by UV headlights to detect pedestrians is striking.

5.4 VISIBILITY EFFECT ON STOPPING SIGHT DISTANCE

If a vehicle is traveling at a constant velocity, and it is assumed that an instantaneous braking level is applied to stop the vehicle in order to avoid an obstacle or stop at a stopping line, there is an associated minimum distance that the vehicle requires in order to stop. This minimum-required stopping distance can be obtained from the equation:

$$D_{min\ stop} = \frac{V^2}{2a} \tag{5}$$

where

$D_{min\ stop}$ = minimum required stopping distance, ft
V = constant velocity , ft/s
a = braking acceleration, ft/s^2

The distance that the vehicle travels during driver and system delays is added to this equation to get the total distance a vehicle will travel before coming to a stop:

$$D_{stop} = Vt_d + \frac{V^2}{2a} \tag{6}$$

where

D_{stop} = total stopping distance, ft
t_d = time due to driver and system delays, s

```
Driver age: 35    Percent Accomodated: 50
Road geometry file: GE00.DAT
Target type: Pedestrian
Target size:  3.4 minutes

Observer Car Lamps: LOWBEAM.LMP   (Symetrical two-lamp system)
CP on target:  5601    Illumination at target:  0.000 fc
Background luminance: 51.0000 fl   Target luminance: 85.0000 fl
Background reflectance:  0.0600 fl/fc    Target reflectance:  0.1000 fl/fc

Glare CP:      0    Glare angle (minimum):  0.0 degrees
Veiling glare:  0.000   DGF:  1.000   VBF:  0.000
DeBoer glare index (w):   0.000

C.VL:  1.000    VL: 13.515    DELTA.XT:  100
Seeing distance: 4300 feet


Press 'Q' to quit, 'L' to see locations,  any other key to continue
```

Locations* and Aim of Driver, Driver Lamps, Glare Lamps and Target

	distance	lateral location	height	horiz aim	vert aim	lampfile
Driver	-2806	-7.5	3.5	0.0	0.0	
d-lamp	-2800	-8.0	2.0	0.0	0.0	lowbeam.lmp
d-lamp	-2800	-4.0	2.0	0.0	0.0	lowbeam.lmp
Target	1500	2.0	0.0	0.0	0.0	Pedestrian

* Locations and aim are measured with respect to the start of the road segment(x), the right edge of the right lane (y) and the road surface (z).

Press any key to continue

Figure 5-3. Screen Dumps Illustrating a Daylight Seeing Distance Condition and the Range of Parameters

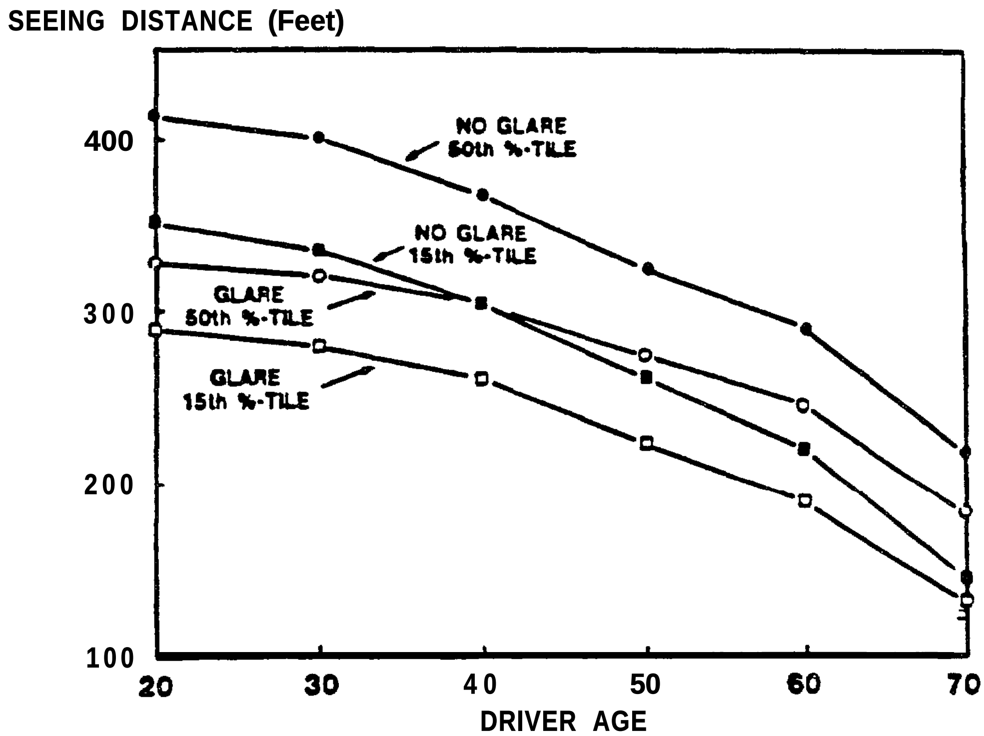


Figure 5-4. Sensitivity of Seeing Distances to Glare, Age, and Percentile Contrast Sensitivity

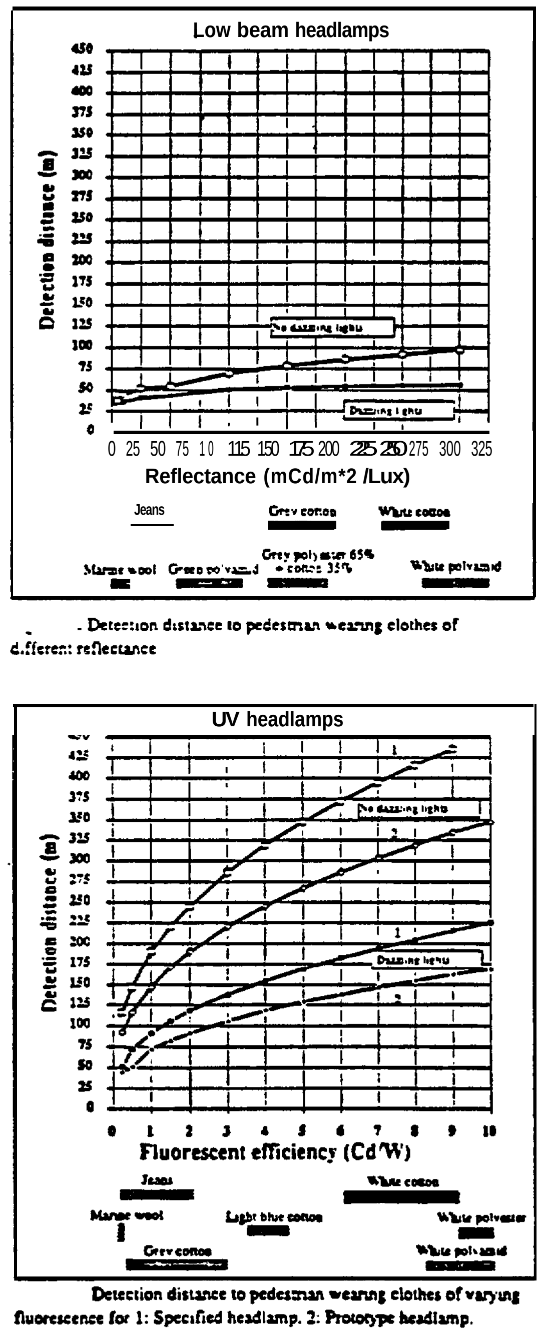


Figure 5-5. PCDETECT Simulation Results Comparing UV Headlights with Low Beam Headlights on Sight Distance (Source: Fast & Ricksand, 1994)

Refer to Figure 5-6. Suppose the normal visibility sight distance is approximately 650 ft. Given a car traveling at a constant velocity of 88 ft/s (60 mph) and a normal braking level of 11.7 ft/s^2, the minimum stopping distance required is about 330 ft. This leaves approximately 3.6 seconds for driver and system delays. If a more aggressive braking level of 16 ft/s^2 is applied, then the minimum stopping distance is decreased to 242 ft and delay time is increased to about 4.6 s.

Under reduced visibility conditions, if the sight distance is only 330 ft and the previous velocity and the normal braking level are maintained, then the minimum stopping distance remains unchanged from the above example, but the time left for driver and system delays has been eliminated. If the emergency braking level is applied, the minimum stopping distance remains unchanged from the previous example at 242 ft, but the time budget for delays is now only 1.0 s.

5.5 CONCLUSIONS

Traffic engineers use various sight distances in planning and laying out roadways (Neuman, 1992). Stopping Sight Distance is the distance a driver needs to see an object and stop in time to avoid crashing into that object. Table 5-2 provides stopping sight distance design requirements currently used by traffic engineers. This table provides recommended sight distance ranges based on design speed of the roadway, assumed travel speed, a 2.5 s brake reaction time, various coefficients of friction assumed for braking. The values are essentially derived from an equation like Equation (6). These range from approximately 125 ft to 850 ft.

Passing Sight Distance refers to that distance made available to drivers on two-lane highways to pass slower moving vehicles. Table 5-3 provides passing sight distance design requirements as a function of prevailing speed and whether the vehicle being passed is a passenger car or a truck. As might be expected from the passing maneuver, the sight distances recommended are generally longer than stopping sight distances, ranging from 325 ft (at 20 mph) to over 2,500 ft (for prevailing travel speeds of 70 mph).

Decision Sight Distance is that distance required for a driver to perceive an unexpected or complex situation, arrive at a decision regarding a course of action, and execute that decision in a reasonable manner. Table 5-4 provides decision sight distances as a function of various design speeds and assuming various avoidance maneuvers. These values range from a low of 220 ft for a simple braking maneuver on a rural road from a 30 mph approach to 1,525 ft for braking at an urban road from a 70 mph approach.

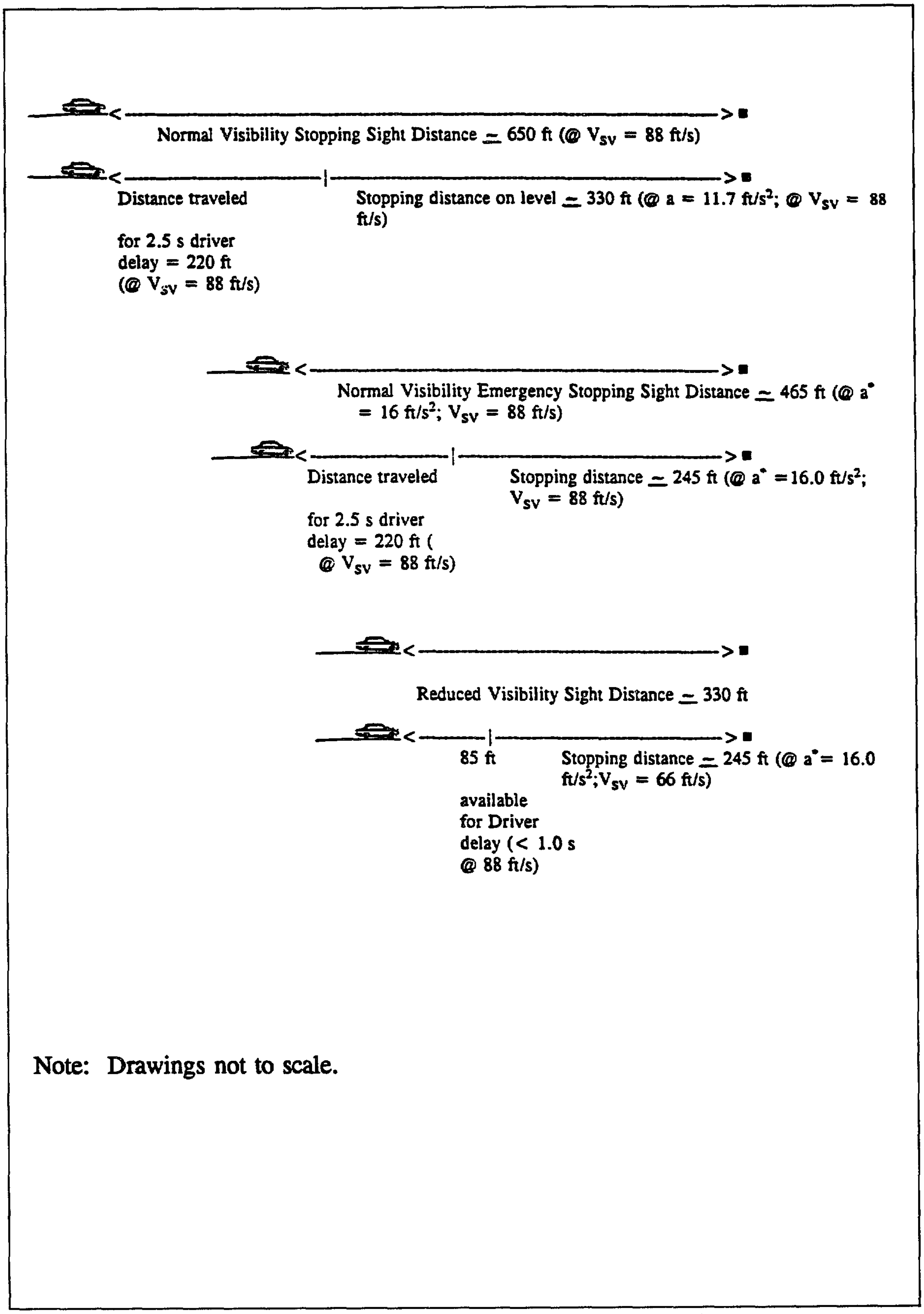


Figure 5-6. Visibility Impact on Stopping Sight Distance

Table 5-2*
Stopping Sight Distance Design Requirements

Design Speed (mph)	Assumed Speed for Condition (mph)	Brake Reaction Time (sec)	Brake Reaction Distance (ft)	Coefficient of Friction f	Braking Distance on Level[a] (ft)	Stopping Sight Distance Computed[a] (ft)	Stopping Sight Distance Rounded for Design (ft)
20	20-20	2.5	73.3-73.3	0.40	33.3-33.3	106.7-106.7	125-125
25	24-25	2.5	88.0-91.7	0.38	50.5-54.8	138.5-146.5	150-150
30	28-30	2.5	102.7-110.0	0.35	74.7-85.7	177.3-195.7	200-200
35	32-35	2.5	117.3-128.3	0.34	100.4-120.1	217.7-248.4	225-250
40	36-40	2.5	132.0-146.7	0.32	135.0-166.7	267.0-313.3	275-325
45	40-45	2.5	146.7-165.0	0.31	172.0-217.7	318.7-382.7	325-400
50	44-50	2.5	161.3-183.3	0.30	215.1-277.8	376.4-461.1	400-475
55	48-55	2.5	176.0-201.7	0.30	256.0-336.1	432.0-537.8	450-550
60	52-60	2.5	190.7-220.0	0.29	310.8-413.8	501.5-633.8	525-650
65	55-65	2.5	201.7-238.3	0.29	347.7-485.6	549.4-724.0	550-725
70	58-70	2.5	212.7-256.7	0.28	400.5-583.3	613.1-840.0	625-850

[a]Different values for the same speed result from using unequal coefficients of friction.

Table 5-3*
Passing Sight Distance Design Requirements

Design or Prevailing Speed (mph)	Passing Sight Distance (ft) as given by AASHTO Policy	Passing Sight Distance (ft) as given by MUTCD[a] Criteria	Passing Sight Distance (ft) for Passenger Car Passing Passenger Car	Passing Sight Distance (ft) for Passenger Car Passing Truck
20	800	—	325	350
30	1,100	500	525	575
40	1,500	600	700	800
50	1,800	800	875	1,025
60	2,100	1,000	1,025	1,250
70	2,500	1,200	1,200	1,450

[a]*Manual on Uniform Traffic Control Devices for Streets and Highways.*

Table 5-4*
Decision Sight Distances

Design Speed (mph)	Decision Sight Distance for Avoidance Maneuver (ft) A	B	C	D	E
30	220	500	450	500	625
40	345	725	600	725	825
50	500	975	750	900	1,025
60	680	1,300	1,000	1,150	1,275
70	900	1,525	1,100	1,300	1,450

The following are typical avoidance maneuvers covered in the above table.
- Avoidance Maneuver A: Stop on rural road.
- Avoidance Maneuver B: Stop on urban road.
- Avoidance Maneuver C: Speed/path/direction change on rural road.
- Avoidance Maneuver D: Speed/path/direction change on suburban road.
- Avoidance Maneuver E: Speed/path/direction change on urban road.

*Source: Neuman, (1992).

Finally, Intersection Sight Distances are intended to provide sufficient unobstructed view to permit control of the vehicle to avoid a crash. Intersection sight distances are broken down into four different subtypes:

- I No control, with vehicles adjusting speeds to avoid collision;
- II Yield control, with vehicles on the minor roadway yielding to the major roadway;
- III Stop (sign) control on the minor roadway; and
- IV Signal control.

Neuman (1992) points out that Class III and IV intersections are most common and that Class III intersections represent the most safety-critical conditions generally encountered. Figure 5-7 presents a nomograph for Class IIIA intersection sight distance for crossing a major roadway from the stop. The nomograph provides sight distances as a function of vehicle type and the width of the roadway being crossed. These values range from a low of 200 ft for a ‘L-lane road at a design speed of 20 mph to over 1700 ft for a 4-lane divided road with a 60-inch median and design speeds of 70 mph.

These various traffic engineering design guidelines may be useful for determining the range of visibility enhancement systems. A system that can provide a range of, say, 1,600 ft would be robust for many different driving circumstances provided the driver drives 60 mph or less. A system that cannot provide a range of at least 125 ft is likely to be useless for even the most benign of driving circumstances.

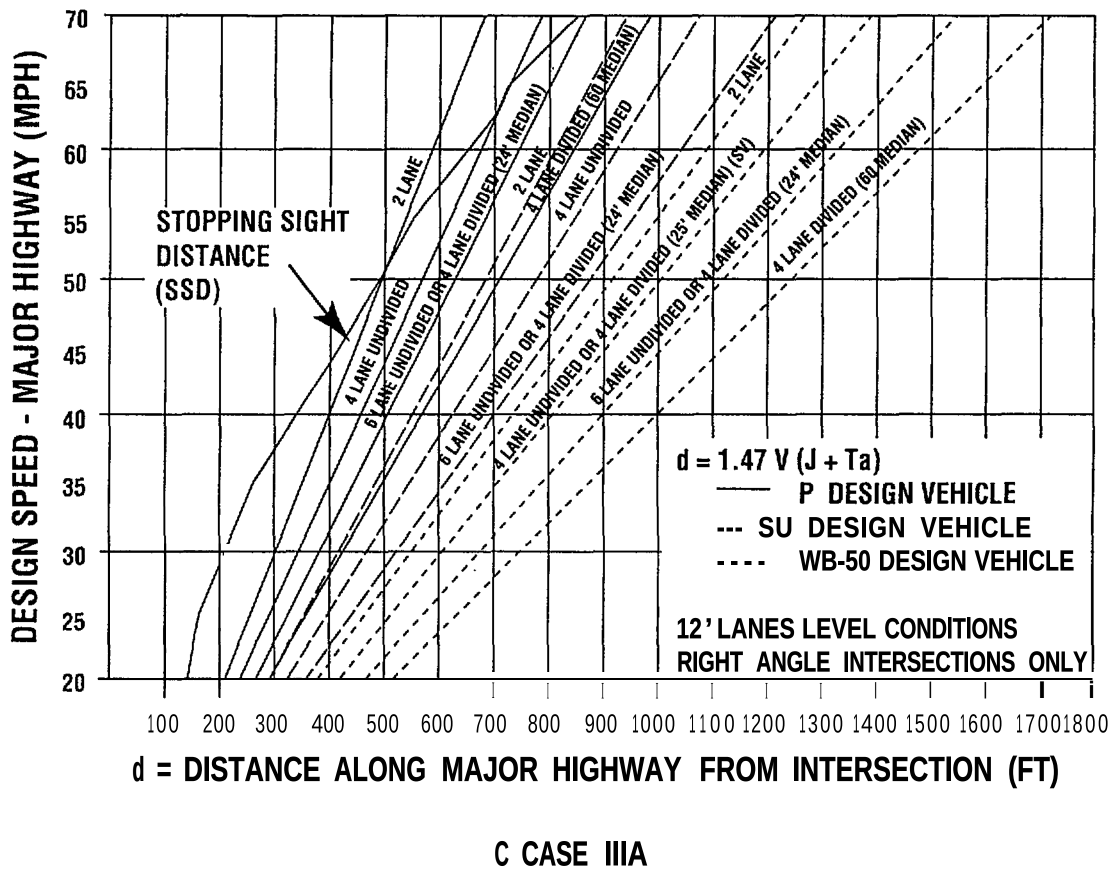


Figure 5-7. Class IIIA Intersection Sight Distance Requirements (Source: Newman, 1992.)

6. RESEARCH NEEDS

6.1 INTRODUCTION

This section describes some of the research needs and unresolved issues that surround the reduced visibility problem. General research needs are presented, followed by a section describing more specific research needs that focus on the potential consequences of providing drivers with enhanced information about the driving environment. Finally, because many current technological devices are based on research in aviation, the last section describes some of the important differences between aviation and driving.

6.2 PROBLEM DEFINITION RESEARCH NEEDS

- There is a lack of data as to the magnitude of the reduced visibility crash problem. Part of the difficulty in accurately sizing the reduced visibility problem relates to the presence of potentially confounding variables (e.g., driver fatigue at night, poor traction in bad weather, driver intoxication). In addition, driver reports must be used to attempt to ascertain if reduced visibility was the main problem; these are not always accessible from mass crash databases. Even those that are available must be scrutinized for their veracity. At a minimum it would be instructive to replicate the analysis included in this report mindful of the need to rigorously document the sampling in order to better assess the target crash problem size in relation to all crashes. This might include an expanded sample to include crashes occurring before 9 pm to capture dusk and perhaps early night conditions.

- To extend the work of Owens and Sivak, it would be beneficial if statistical methods were developed or identified to partition out the various factors that might contribute to crashes in “not clear day” conditions. This might provide further insights into the reduced visibility problem size and the nature of how it affects various crash circumstances. An analysis of variance (ANOVA) approach, for instance, might be developed to assess the relative contributions of reduced visibility, fatigue, traction, intoxication, or combinations thereof to crash incidence.

- Some reduced visibility crash types were not represented in the clinical sample analyzed for this report because the original intent of the CDS database was to support crashworthiness research. Examples of crashes that were not represented in the clinical sample include pedestrian mishaps and animal strikes. These types of mishaps are nonetheless a key source of reduced visibility crashes.

6.3 REDUCED VISIBILITY MODEL DEVELOPMENT NEEDS

- A useful model for automotive applications would combine the effects of low-ambient illumination and atmospheric obscurants on seeing or sight distances. Using the most recent extensions of Blackwell's threshold contrast research, PCDETECT seems a logical program to extend in this direction and incorporate luminance formulas from VI/FOG or other models. This would allow for a broader range of modeling assessments for the anticipated seeing distances in, say, daylight with dense fog versus night with dense fog. This model development should also include establishment of threshold contrast data for the driving situation. This would include appropriate factors for age, surprise, target shape and size for objects common to driving, automobile reflectance and tail light sources, and presentation times characteristic of driver eye scanning patterns. Some of these factors have already been incorporated into PCDETECT but others have not.

6.4 HUMAN FACTORS RESEARCH NEEDS

- An important research issue concerns the types of information that need to be provided to the driver. Reduced visibility has its greatest impact by reducing the visual information available to the driver. The types of visual information used to control a vehicle were only briefly mentioned in this report. Optical flow, looming, contrast, object visual size, and other forms of information play a critical role in enabling drivers to effectively assess situations and control their vehicles. Reductions in this information have as-yet-unknown effects on driver effectiveness, yet it is this information that is to be replaced by displays and warning devices.

- There is a need to assess potential secondary consequences of reduced visibility countermeasures or visibility enhancement systems. To appreciate what these secondary consequences might be, consider the following example (Ervin, 1994). On a foggy night, one driver of a vehicle without reduced visibility countermeasures is waiting at a stop sign on a side street to make a left turn onto a major road. In the distance, this driver notices the dim headlights of an approaching car. Expecting that no one would be driving at high speeds with such poor visibility, the driver on the side street begins to pull out. Too late, that driver realizes the approaching vehicle is indeed traveling very fast and a crash ensues. The approaching vehicle, it turns out, was equipped with reduced visibility countermeasures that allowed its driver to travel at higher speeds. The hapless driver on the side street made use of expectancies developed through past experience that did not, and could not take this new technology into account. Is this problem (and others that typify "secondary" safety consequences) a red herring or a legitimate concern? Only further investigation will tell.

- There is a need to assess the workload effects of reduced visibility countermeasures. For example, an in-vehicle video display of the road scene ahead may prove to be unacceptable because of the visual demand it places on the driver. The driver will have to visually focus on the video image and, therefore, take eyes off the road scene ahead. The video image will likely not contain all of the information that the driver might pick up by looking directly ahead, especially at closer distances. This effect of diverted visual attention could lead to adverse safety consequences. For example, averting the driver's gaze into the vehicle might disrupt ambient vision, thereby leading to a crash or increased crash risk. This problem might arise if the location of the visual display makes unavailable optical information needed for lane keeping and heading control. It should also be mentioned that apart from video situation displays, even simple warnings might inadvertently take the driver's eyes off the road or hand off the wheel at precisely the wrong time, i.e., during the critical pre-crash period that results in crash avoidance or crash occurrence.

- The issues of interface design for driver performance, acceptance, and system reliability need to be assessed. Reduced visibility countermeasures must accommodate driver preferences as well as compensate for limitations. Drivers might, for example, reject computer-generated icons that are superimposed on real-world objects not visible to the naked eye due to reduced visibility conditions. There is a need to conduct sensitivity analyses on driver interface design parameters for performance and preference effects. For example, the HUD icon superimposed over the real-world object may need to be superimposed within a minimum time delay for icon/object separation. Otherwise, the visual sheer caused by such delays may undermine driver performance or prove to be unacceptable to the driver. There is also a need to conduct failure modes and effects analyses to better understand the implications of CAS system failures under various conditions.

- Human factors research into driver warnings and the false alarm problem have been alluded to in many reports. This problem remains for the reduced visibility situation as well. Research into driver behavior under these conditions is warranted. For example, one might speculate that drivers visually verify the hazard after warning onset. In reduced visibility conditions this may not be possible. What will the driver do?

6.5 VISION ENHANCEMENT SYSTEM RESEARCH NEEDS

- Discussion of sensor technologies are provided in other reports referenced earlier. However, it appears that significant research must be pursued in imaging sensor performance and sensor data processing. Sensor technology

R&D faces the challenge of dealing with all types of weather (e.g., snow) and achieving a low enough device cost to ensure positive cost benefits. This has prompted at least one researcher to question the viability of robust imaging vision enhancement systems for cars and trucks in the near future (Hahn, 1994).

- It is possible, in principle, to have an in-vehicle driver display for an imaging vision enhancement system. Potential problems associated with such in-vehicle sensor image displays include attentional load that competes with the primary task of safely controlling the vehicle at all times, inadequate information transmission to support crash avoidance and driving tasks, difficulties in positioning the device into an already crowded instrument panel, and problems with use of small screen displays. Research is needed to determine necessary and sufficient design parameters for in-vehicle imaging displays in terms of display resolution, display size, displayed field-of-view and range, and on-screen target size, among others.

- It is possible that HUDs might substantially improve highway safety by minimizing eye travel times and improving object and event detection. Comparisons of head-up versus head-down displays typically show HUD superiority for object and event detection (Okabayashi, et al., 1989; Sojourner and Antin, 1990). Automotive HUDs have also been shown to enhance driver-vehicle performance in steering (Weihrauch, Meloeny, and Goesch, 1989) and subjects prefer the HUD over conventional displays even if performance is not affected (Kiefer, 1990). However, a limited number of studies of contact-analogue HUDs for vision enhancement have pointed to potential problems that merit further research. These range from increased driving speed for simulated “ideal” systems to increased workload and decreased attention to targets outside the “eye box.” Research into the necessary and sufficient HUD design parameters for crash avoidance and driving maneuvers is warranted.

APPENDIX A. CASE WEIGHTING SCHEME

The crashes used in the clinical analysis were weighted for severity so that they might more closely approximate the national profile. The weighting procedure – illustrated in Tables A-l, A-2, A-3, A-4, A-5, and A-6 of Appendix A – included the following steps'[1]:

- The crashes in each data set were sorted by severity [Crash Severity]. The number of each in the sample [# in Sample] was compared to the total sample, which gave analysts the percent of the clinical sample represented by each severity [% of Clinical Sample].

- NHTSA provided the percentage of the GES data represented by each severity level [% of 1991 GES].

- The percent of the national profile that each case represented [% Rep. Each Case] was determined by dividing [% of 1991 GES] by [# in Sample].

The following notes apply for Tables A-l through A-6:

1) GES crash severity based on cases involving all vehicle types. Cases of unknown severity were counted as "0" cases.

2) There was an implicit assumption that, within each severity level, the GES PAR Sample was representative of the national crash experience. There were no biases in the GES PAR case selection process.

3) Severity levels 3 and 4 (A and K) were combined because of the small number of 4 (K) severity crashes.

4) % Represented by Each Case is the ratio (% of 1991 GES)/(# in Sample).

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[1] The phrases enclosed in square brackets refer to headings in the tables – for example, [Crash Severity].

Table A-l
Case Weighting Scheme For Total Case Sample

Crash Severity	# in Sample	% of Clinical Sample	% of 1991 GES	% Rep. Each Case
0(0)	35	36.08	64.09	1.8311
1(C)	28	28.87	17.05	0.6089
2(B)	15	15.46	12.10	0.8067
3/4(A/K)	19	19.59	6.75	0.3553
Total	97	100.00	99.99	

Table A-2
Case Weighting Scheme for Probable Cases

Crush Severity	# in Sample	% of Clinical Simple	% of 1991 GES	% Rep. Each Case
0(0)	14	38.89	64.09	4.5779
l(C)	II	30.56	17.05	1.5500
2(B)	5	13.89	12.10	2.4200
3/4(A/K)	6	16.67	6.75	1.1250
Total	36	100.00	99.99	

Table A-3
Case Weighting Scheme for Possible Cases

Crash Severity	# in Sample	% of Clinical Sample	% of 1991 GES	% Rep. Each Case
0(0)	4	23.53	64.09	16.0225
1(C)	2	11.76	17.05	8.5250
2(B)	4	23.53	12.10	3.0250
3/4(A/K)	7	41.18	6.75	0.9643
Total	17	100.00	99.99	

Table A-4
Case Weighting Scheme for Improbable Cases

Crash Severity	# in Sample	% of Clinical Sample	% of 1991 GES	% Rep. Each Case
0(0)	17	38.64	64.09	3.7700
1(C)	15	34.09	17.05	1.1367
2(B)	6	13.64	12.10	2.0167
3/4(A/K)	6	13.64	6.75	1.1250
Total	44	100.00	99.99	

Table A-5
Case Weighting Scheme For Probable Plus Possible Cases With Unknown

Crash Severity	# in Sample	% of Clinical Sample	% of 1991 GES	% Rep. Each Case
0(0)	18	33.96	64.10	3.5611
1(C)	13	24.53	17.05	0.3115
2(B)	9	16.98	12.10	1.3444
3/4(A/K)	13	24.53	6.75	0.5192
Total	53	**100.00**	**100.00**	

Table A-6
Case Weighting Scheme For Probable Plus Possible Cases Without Unknown

Crash Severity	# in *Sample*	% of Clinical *Sample*	% of 1991 GES	% Rep. Each Case
0(0)	16	42.11	64.10	4.0063
I(C)	8	21.05	17.05	2.1313
2(B)	5	13.16	12.10	2.4200
3/4(A/K)	9	23.68	6.75	0.7500
Total	38	100.0	100.00	

APPENDIX B: REDUCED VISIBILITY CDS CRASH DATA SEVERITY, CAUSAL FACTORS, ACCIDENT TYPE AND TIME OF OCCURRENCE

Table B-l contains the reduced visibility clinical sample cases descriptions in terms of crash severity, causal factors, accident type, and time of occurrence.

Table B-1
Reduced Visibility CDS Crash Case Severity, Causal Factors, Accident Type and Time of Occurance

PSU - Case No.	AIS Severity	Causal Factor	Accident Type (w/ description)	Time
02 - 017	0 (O)	Blinded by glare from sun	20 (Rear - end, forward vehicle moving)	0754
02 - 029	0 (O)	Snow/Ice fell from previous vehicle	00 (No Impact)	1315
02 - 035	1 (C)	Poor visibility due to snow	07 (Left Roadside Departure, Control / Traction Loss)	2215
02 - 041	1 (C)	Hillcrest (Roadway Geometry)	20 (Rear - end, Forward Vehicle Moving)	0930
04 - 019	1 (C)	Vision obstructed by baracades	86 (Intersection Crash - Straight Crossing Path, Striking)	1836
04 - 036	1 (C)	Spun out on snow covered road	66 (Sideswipe / Angle)	0700
04 - 057	2 (B)	Blinded by sun	68 (Turn Across Path - Initial opposite Directions)	1441
04 - 089	0 (O)	Vision obstructed by parked car	87 (Intersection Crash - Straight Crossing Path, struck)	1841
05 - 001	0 (O)	Blinded by sun	68 (Turn Across Path - Initial Opposite Directions)	0859
05 - 002	4 (K)	Failed to negotiate curve	01 (Right Roadside Departure - Drive off Road)	2320
05 - 004	2 (B)	Vision obstructed by other vehicle	68 (Turn Across Path - Initial Opposite Directions)	1654
05 - 005	0 (O)	DUI	50 (Head - on, Lateral Move)	
05 - 006	0 (O)	Driver failed to observe other vehicle	68 (Turn Across Path - Initial Opposite Directions)	0653
05 - 008	0 (O)	Blinded by sun	20 (Rear - end, Forward Vehicle Moving)	1375
05 - 017	1 (C)	Did not see until struck it	01 (Right Roadside Departure, Drive off Road)	1914
05 - 035	1 (C)	Blinded by highbeam headlights	06 (Left Roadside Departure, Drive off Road)	2058
05 - 086	2 (B)	Failed to observe turn in road	07 (Left Roadside Departure, Control/Traction Loss)	2100
06 - 002	0 (O)	Unknown	64 (Sideswipe Angle, Lateral Move)	1700
06 - 011	2 (B)	Hit trash dumpster at curb	12 (Forward Impact - Stationary Object)	2035
06 - 024	0 (O)	Unknown	86 (Intersection Crash - Straight Crossing Path, Struck)	0502
08 - 005	0 (O)	Failed to observe other vehicle	68 (Turn Across Path - Initial Opposite Directions)	1310
08 - 020	1 (C)	Blinded by sun glare	20 (Rear - end, Forward Vehicle Moving)	1711
08 - 025	2 (B)	Car drifted off R side of road	01 (Right Roadway Departure, Drive off Road)	1322
08 - 032	0 (O)	Failed to observe other vehicle	68 (Turn Across Path - Initial Opposite Directions)	0230
08 - 042	0 (O)	Failed to observe other vehicle	78 (Turn Into Path - Turn Into Same Direction)	1504
08 - 055	1 (C)	Blinded by sun	68 (Turn Across Path - Initial Opposite Directions)	1928
08 - 102	0 (O)	Traveling too fast for conditions	02 (Right Roadside Departure, Control/Traction Loss)	0750
09 - 003	4 (K)	Improper passing - hit head on	50 (Head - on, Lateral Move)	2250

Table B-1
Continued

PSU - Case No.	AIS Severity	Causal Factor	Accident Type (w/ description)	Time
09 - 006	2 (B)	Left R side of road	01 (Right Roadside Departure, Drive off Road)	0220
09 - 007	0 (O)	Hit disabled vehicle left in road	20 (Rear - end, Forward Vehicle Moving)	1200
09 - 026	3 (A)	Left road and hit tree	02 (Right Roadside Departure, Control/Traction Loss)	0040
09 - 039	4 (K)	Lost control and impacted guardrail	07 (Left Roadside Departure, Control/Traction Loss)	0403
09 - 042	1 (C)	Run off road (R) side of (L) curve	07 (Left Roadside Departure, Control/Traction Loss)	0026
09 - 046	1 (C)	POV failed to use headlights	98 (Other Accident Type, U - Turn Across Traffic)	2114
09 - 054	3 (A)	Drove off end of dead end street	88 (Intersection Crash - Straight Crossing Path, Striking)	2341
09 - 058	2 (B)	Failed to negotiate curve (R)	06 (Left Roadside Departure, Drive off Road)	0002
09 - 081	3 (A)	Failed to negotiate (R) curve	06 (Left Roadside Departure, Drive off Road)	0230
11 - 022	0 (O)	Hit parked vehicle	20 (Rear - end, Forward Vehicle Moving)	0849
11 - 025	2 (B)	Failed to observe POV	68 (Turn Across Path - Initial Opposite Directions)	1800
11 - 026	1 (C)	Failed to observe POV	68 (Turn Across Path - Initial Opposite Directions)	1800
11 - 032	1 (C)	Drove (L) of center on (L) curve	06 (Left Roadside Departure, Drive off Road)	0020
11 - 047	2 (B)	Crossed over CL in (R) curve	64 (Sideswipe Angle, Lateral Move)	0005
11 - 048	2 (B)	Failed to negotiate (R) curve	06 (Left Roadside Departure, Drive off Road)	0313
11 - 053	4 (K)	Rear - ended semi-trailer	24 (Rear - end, Forward Vehicle Slower)	0358
11 - 054	0 (O)	Struck rear of stopped vehicle	20 (Rear - end, Forward Vehicle Moving)	1739
11 - 055	2 (B)	Attempting to pass line of traffic	50 (Head - on, Lateral Move)	1645
11 - 066	0 (O)	Struck rear end of proceeding vehicle	48 (Sideswipe/Angle, each)	2020
11 - 107	0 (O)	Failed to negotiate (L) curve	50 (Head - on, Lateral Move)	2350
12 - 004	0 (O)	DUI	82 (Turn Into Path - Turn Into Opposite Directions)	0315
12 - 005	1 (C)	Questionable headlight usage	20 (Rear - end, Forward Vehicle Moving)	0541
12 - 010	0 (O)	Proceeding trough Int. - Impacted	86 (Intersection Crash - Straight Crossing Path, Struck)	1730
12 - 013	1 (C)	Failed to observe - windows frosted	82 (Turn Into Path - Turn Into Opposite Directions)	1810
13 - 005	1 (C)	Failed to observe stop sign	68 (Turn Across Path - Initial Opposite Directions)	1155
13 - 006	0 (O)	Lost control in curve	86 (Intersection Crash - Straight Crossing Path, Struck)	0745
13 - 008	4 (K)	Subject veh. pulled into path of POV	66 (Sideswipe / Angle, each)	2322
13 - 009	4 (K)	DUI	82 (Turn Into Path - Turn Into Opposite Directions)	0113

Table B-1
Continued

PSU - Case No.	AIS Severity	Causal Factor	Accident Type (w/ description)	Time
13 - 017	1 (C)	Failed to negotiate (R) curve	01 (Right Roadside Departure, Drive off Road)	0753
13 - 020	4 (K)	Lost control or failed to detect (R) curve	01 (Right Roadside Departure, Drive off Road)	2330
13 - 066	0 (O)	DUI	06 (Left Roadside Departure, Drive off Road)	0200
13 - 067	1 (C)	Failed to observe POV	07 (Left Roadside Departure, Control/Traction Loss)	1510
13 - 074	1 (C)	Failed to observe POV	88 (Intersection Crash - Straight Crossing Path, Striking)	2125
13 - 077	1 (C)	Flaied to observe Int. / stop sign	20 (Rear - end, Forward Vehicle Moving)	0955
13 - 086	1 (C)	Failed to observe POV	88 (Intersection Crash - Straight Crossing Path, Striking)	1517
13 - 088	0 (O)	Failed to observe POV	86 (Intersection Crash - Straight Crossing Path, Struck)	1615
13 - 089	1 (C)	Failed to observe POV	68 (Turn Across Path - Initial Opposite Directions)	1814
13 - 093	1 (C)	Failed to observe other vehicle	68 (Turn Across Path - Initial Opposite Directions)	1939
13 - 109	3 (A)	Approached curve too fast	01 (Right Roadside Departure, Drive off Road)	0250
13 - 114	0 (O)	Blinded by glare from sun	68 (Turn Across Path - Initial Opposite Directions)	1858
13 - 119	0 (O)	Lost control on curve	07 (Left Roadside Departure, Control/Traction Loss)	2200
13 - 138	0 (O)	Vehicle driving without headlights	68 (Turn Across Path - Initial Opposite Directions)	2300
13 - 143	0 (O)	Lost control on (L) curve entrance ramp	02 (Right Roadside Departure, Control/Traction Loss)	1245
13 - 152	1 (C)	Lost control on (R) curve exit ramp	07 (Left Roadside Departure, Control/Traction Loss)	2135
43 - 002	4 (K)	Failed to observe POV	82 (Turn Into Path - Turn Into Opposite Directions)	1816
43 - 004	1 (C)	POV pulled out into traffic	82 (Turn Into Path - Turn Into Opposite Directions)	2030
43 - 011	3 (A)	Failed to yield at T-Intersection	78 (Turn Into Path - Turn Into Same Direction)	2145
43 - 018	1 (C)	Lost control (hydroplane)	07 (Left Roadside Departure, Control/Traction Loss)	1537
43 - 027	2 (B)	Vehicle ran off (R) side of road	06 (Left Roadside Departure, Drive off Road)	0623
43 - 036	3 (A)	Rear - ended disabled vehicle	20 (Rear - end, Forward Vehicle Moving)	2242
43 - 044	unknown	Exited sharp curve - too much speed	02 (Right Roadside Departure, Control/Traction Loss)	2000
43 - 045	2 (B)	Exited (L) curve on (R) side - Exc. speed	02 (Right Roadside Departure, Control/Traction Loss)	2358
43 - 046	3 (A)	Hit water puddle - lost control	64 (Sideswipe Angle, Lateral Move)	2120
43 - 055	0 (O)	Failed to observe POV (Stopped vehicle)	98 (Other Accident Type, U - Turn Across Traffic)	2112
43 - 064	1 (C)	Failed to observe POV	87 (Intersection Crash, Straight Crossing Path, Struck)	1429
43 - 092	2 (B)	Exited (R) curve at high speed	07 (Left Roadside Departure, Control/Traction Loss)	0359

Table B-1
Continued

PSU - Case No.	AIS Severity	Causal Factor	Accident Type (w/ description)	Time
43 - 093	0 (O)	Failed to observe POV	89 (Intersection Crash, Straight Crossing Path, Struck)	1350
43 - 103	1 (C)	Improper passing maneuver	64 (Sideswipe Angle, Lateral Move)	2130
43 - 104	1 (C)	Blinded by headlights	01 (Right Roadside Departure, Drive off Road)	0100
43 - 105	3 (A)	Exited (R) curve, hit trees	02 (Right Roadside Departure, Control/Traction Loss)	2240
45 - 002	0 (O)	Lost control in (R) curve	02 (Right Roadside Departure, Control/Traction Loss)	0108
45 - 004	3 (A)	Entered curve at high speed, exited	06 (Left Roadside Departure, Drive off Road)	2140
45 - 034	0 (O)	Rear end proceeding vehicle	20 (Rear - end, Forward Vehicle Moving)	1920
45 - 039	0 (O)	Ran off (R) side of road	01 (Right Roadside Departure, Drive off Road)	0020
45 - 045	3 (A)	Rear ended semi-trailer	11 (Forward Impact - Parked Vehicle)	2043
45 - 070	2 (B)	Ran off (R) side of straight road	02 (Right Roadside Departure, Control/Traction Loss)	2220
45 - 071	4 (K)	Ran off (R) side of road	01 (Right Roadside Departure, Drive off Road)	2029
45 - 073	0 (O)	Failed to observe headlights	82 (Turn Into Path - Turn Into Opposite Directions)	2001
45 - 115	0 (O)	Poor visibility (roadway geometry)	68 (Turn Across Path - Initial Opposite Directions)	2205

APPENDIX C. CDS GENERAL VEHICLE FORM CLUSTER OF COLLISION AVOIDANCE VARIABLES

The cluster variables consist of a five-variable sequence located in the NASS CDS General Vehicle Form. These variables generally describe the pre-crash vehicle movement pattern, driver actions, and results of these actions. The variables in the sequence are:

- GV 14 Attempted Avoidance Maneuver
- GV 64 Pre-event Movement (Prior to Recognition of Critical Event)
- GV 65 Critical Pre-crash Event
- GV 66 Pre-crash Stability After Avoidance Maneuver
- GV 67 Pre-crash Directional Consequences of Avoidance Maneuver (Corrective Action)

A key that describes the codes used for each of these variables is provided below.

Table C-l presents the originally-coded cluster variable data for the CDS cases in the reduced visibility clinical sample. The first column of the table is the Primary Sampling Unit Case Number (PSU Case No.). The next four columns provide data on subject vehicle driver, lighting conditions, weather/surface traction, and speed characteristics of each case. The following five columns contain the data for the sequence of five collision avoidance variables with respect to the Subject Vehicle (SV). The last column contains the classification of reduced visibility involvement,

GV14
Attempted Avoidance Maneuver

00	No impact
01	No avoidance actions
02	Braking (no lockup)
03	Braking (lockup)
04	Braking (lockup unknown)
05	Releasing brakes
06	Steering left
07	Steering right
08	Braking and steering left
09	Braking and steering right
10	Accelerating
11	Accelerating and steering left
12	Accelerating and steering right
97	No driver present
98	Other action (specify)
99	Unknown

GV64
Pre-Event Movement (Prior to recognition of Critical Event)

01	Going straight
02	Slowing or stopping in traffic lane
03	Starting in traffic lane
04	Stopped in traffic lane
05	Passing or overtaking another vehicle
06	Disabled or parked in travel lane
07	Leaving a parking position
08	Entering a parking position
09	Turning right
10	Turning left
11	Making a U-turn
12	Backing up (other than for parking position)
13	PTegotiating a curve
14	Changing lanes
15	Merging
16	Successful avoidance maneuver to a previous critical event
97	Other (specify):
98	No driver present
99	Unknown

GV65
Critical Prewash Event

This Vehicle Loss of Control Due To:

01 Blow out or flat tire
02 Stalled engine
03 Disabling vehicle failure (e.g., wheel fell off) (specify):
04 Non-disabling vehicle problem (e.g., hood flew up) (specify)
05 Poor road conditions (puddle, pot hole, ice, etc.) (specify)
06 Traveling too fast for conditions
08 Other cause of control loss (specify)
09 Unknown cause of control loss

This Vehicle Traveling

10 Over the lane line on left side of travel lane
11 Over the lane line on right side of travel lane
12 Off the edge of the road on the left side
13 Off the edge of the road on the right side
14 End departure
15 Turning left at intersection
16 Turning right at intersection
17 Crossing over (passing through) intersection
19 Unknown travel direction

Other Motor Vehicle In Lane

50 Stopped
51 Traveling in same direction with lower speed (i.e., lower steady speed or deceleration)
52 Traveling in same direction with higher speed
53 Traveling in opposite direction
54 In crossover
55 Backing
59 Unknown travel direction of other motor vehicle in lane

Other Motor Vehicle Encroaching Into Lane

60 From adjacent lane (same direction) - over left lane line
61 From adjacent lane (same direction) - right lane line
62 From opposite direction - over left lane line
63 From opposite direction - over right lane line
64 From parking lane
65 From crossing street, turning into same direction
66 From crossing street, across path
67 From crossing street, turning into opposite direction
68 From crossing street, intended path not known
70 From driveway, turning into same direction
71 From driveway, across path
72 From driveway, turning into opposite direction
73 From driveway, intended path not known
74 From entrance to limited access highway
78 Encroachment by other vehicle - details unknown

Pedestrian or Pedalcyclist, or Other Nonmotorist

80 Pedestrian in roadway
81 Pedestrian approaching roadway
82 Pedestrian - unknown location
83 Pedalcyclist or other nonmotorist in roadway (specify)
84 Pedalcyclist or other nonmotorist approaching roadway (specify)
85 Pedalcyclist or other nonmotorist - unknown location (specify)

Object or Animal

87 Animal in roadway
88 Animal approaching roadway
89 Animal - unknown location
90 Object in roadway
91 Object approaching roadway
92 Object - unknown location
98 Other critical precrash event
(specify) :
99 unknown

GV66
Prewash Stabiity After Avoidance Maneuver

0 No avoidance maneuver
1 Tracking
2 Skidding longitudinally - less than 30 degrees rotation .
3 Skidding laterally - clockwise rotation
4 Skidding laterally - counterclockwise rotation
7 Other vehicle loss-of-control (specify)
8 No driver present
9 Recrash stability unknown

GV67
Prewash Directional Consequences of Avoidance Maneuver (Corrective Action)

0 No avoidance maneuver
1 Vehicle stayed in travel lane where avoidance maneuver was initiated
2 Vehicle stayed on roadway but left travel lane where avoidance maneuver was initiated
3 Vehicle stayed on roadway, not known if left travel lane where avoidance maneuver was initiated
4 Vehicle departed roadway
5 Avoidance maneuver initiated off roadway
8 No driver present
9 Directional consequences unknown

Table C-1
Reduced Visibility CDS Data

PSU - Case No.	Subject Driver	Light Conditions	Weather / Surface	Speed Limit	GV 14	GV 64	GV65	GV 66	GV 67	Classification
02 - 017	32 / F	daylight	clear / dry	30	02	03	50	1	1	Improbable
02 - 029	34 / M	daylight	clear / dry	55	99	01	98	9	9	Improbable
02 - 035	28 / F	dark	snow / ice	55	99	01	05	9	9	Possible
02 - 041	23 / M	daylight	rain / wet	40	99	01	50	9	9	Probable
04 - 019	28 / M	dark - lighted	clear / dry	40	01	01	66	0	0	Probable
04 - 036	23 / F	daylight	snow / snow	40	07	13	05	4	2	Probable
04 - 057	87 / M	daylight	clear / dry	40	99	13	15	9	9	Improbable
04 - 089	66 / M	daylight	clear / dry	25	99	01	17	9	9	Improbable
05 - 001	17 / M	daylight	clear / dry	35	01	13	15	0	0	Possible
05 - 002	27 / F	dark	clear / dry	35	01	13	13	0	0	Probable
05 - 004	18 / M	dark - lighted	rain / wet	35	99	02	15	9	9	Probable
05 - 005	54 / M			45	01	02	10	0	0	Improbable
05 - 006	49 / M	dark - lighted	rain / wet	45	01	02	15	0	0	Probable
05 - 008	75 / F	daylight	clear / dry	35	01	01	50	0	0	Probable
05 - 017	36 / F	dark - lighted	clear / dry	35	01	13	13	0	0	Improbable
05 - 035	19 / M	dark	clear / dry	40	03	13	12	2	4	Probable
05 - 086	16 / M	dark	clear / dry	35	03	13	06	2	4	Probable
06 - 002	20 / F	dark	clear / dry	55	99	16	10	9	9	Improbable
06 - 011	24 / M	dark - lighted	rain	35	99	01	11	9	9	Probable
06 - 024	48 / M	dark - lighted	rain / wet	35	08	01	66	1	1	Improbable
08 - 005	23 / F	daylight	clear / dry	35	99	13	15	9	9	Improbable
08 - 020	35 / M	daylight	clear / dry	45	01	02	50	0	0	Improbable
08 - 025	80 / M	daylight	snow / wet	35	01	13	13	0	0	Improbable
08 - 032	38 / M	dark - lighted	clear / dry	25	08	03	15	2	1	Probable
08 - 042	18 / F	daylight	clear / dry	40	01	02	16	0	0	Improbable
08 - 055	62 / M	daylight	clear / dry	25	01	02	15	0	0	Improbable
08 - 102	47 / M	daylight	rain / wet	55	06	01	05	2	4	Probable
09 - 003	43 / M	dark - lighted	rain / wet	30	99	05	10	9	9	Probable

Table C-1
Continued

PSU - Case No.	Subject Driver	Light Conditions	Weather / Surface	Speed Limit	GV 14	GV 64	GV65	GV 66	GV 67	Classification
09 - 006	19 / F	dark	clear / dry	50	01	01	13	0	0	Probable
09 - 007	61 / M	daylight	clear / dry	55	04	01	50	1	1	Improbable
09 - 026	21 / M	dark	clear / dry	50	08	13	05	3	4	Probable
09 - 039	47 / M	dark	cloudy / dry	99	99	13	12	9	9	Improbable
09 - 042	29 / M	dark	cloudy / dry	45	99	13	06	9	9	Probable
09 - 046	47 / M	dark	cloudy / dry	35	99	02	15	9	9	Probable
09 - 054	18 / M	dark - lighted	cloudy / dry	50	01	01	17	0	0	Possible
09 - 058	24 / F	dark	rain / wet	55	99	13	12	9	9	Possible
09 - 081	18 / M	dark	cloudy / dry	30	99	13	12	9	9	Possible
11 - 022	32 / M	daylight	sleet / wet	25	02	13	50	1	3	Improbable
11 - 025	55 / M	dark - lighted	clear / dry	30	01	02	15	0	0	Improbable
11 - 026	68 / F	daylight	clear / dry	25	01	02	15	0	0	Improbable
11 - 032	38 / M	dark	clear / dry	45	01	13	12	0	0	Probable
11 - 047	48 / F	dark	cloudy / snow	55	99	13	05	9	9	Possible
11 - 048	20 / M	dark	clear / icy	25	03	13	12	3	4	Improbable
11 - 053	42 / M	dark	windy / wet	55	99	01	51	9	9	Possible
11 - 054	26 / F	daylight	blowing snow / snow	35	99	01	50	9	9	Probable
11 - 055	25 / M	daylight	blowing snow / snow	50	99	05	10	9	9	Improbable
11 - 066	20 / F	dark	snow / snow / icy	55	01	02	05	0	0	Possible
11 - 107	44 / F	dark	rain	45	01	13	10	0	0	Probable
12 - 004	34 / M	dark	blowing snow / snow	65	99	01	50	9	9	Probable
12 - 005	54 / M	dark - lighted	rain	35	01	03	66	0	0	Probable
12 - 010	26 / M	dark - lighted	blowing snow / snow	45	01	03	15	0	0	Probable
12 - 013	16 / M	dark - lighted	cloudy / dry	55	01	03	15	0	0	Probable
13 - 005	25 / M	daylight	rain / wet	25	07	01	17	1	1	Improbable
13 - 006	23 / M	daylight	blowing snow / snow	55	99	13	05	9	9	Improbable
13 - 008	17 / M	dark - lighted	cloudy / wet	45	99	03	15	9	9	Probable
13 - 009	22 / F	dark	cloudy / snow	55	06	13	13	1	4	Possible

Table C-1
Continued

PSU - Case No.	Subject Driver	Light Conditions	Weather / Surface	Speed Limit	GV 14	GV 64	GV65	GV 66	GV 67	Classification
13 - 017	21 / F	daylight	clear / dry	65	01	13	13	0	0	Improbable
13 - 020	34 / M	dark	clear / dry	45	09	13	06	3	4	Improbable
13 - 066	37 / M	dark	clear / dry	65	07	01	05	3	4	Probable
13 - 067	46 / F	daylight	clear / dry	55	01	01	17	0	0	Improbable
13 - 074	17 / F	dark	snow / ice	50	02	01	50	1	1	Improbable
13 - 077	31 / F	daylight	cloudy / dry	55	01	01	17	0	0	Probable
13 - 086	17 / F	daylight	clear / dry	25	99	02	15	9	9	Improbable
13 - 088	52 / M	daylight	cloudy / dry	25	06	01	17	1	1	Improbable
13 - 089	19 / M	daylight	clear / dry	45	01	02	15	0	0	Improbable
13 - 093	18 / M	daylight	clear / dry	55	01	01	15	0	0	Improbable
13 - 109	35 / M	dark	rain / wet	55	01	13	11	0	0	Possible
13 - 114	16 / M	daylight	daylight	40	01	02	15	0	0	Improbable
13 - 119	20 / M	dark	rain / wet	65	03	13	06	4	4	Improbable
13 - 138	19 / F	dark - lighted	clear / dry	45	01	01	15	0	0	Probable
13 - 143	24 / M	daylight	rain / wet	55	06	13	05	3	4	Improbable
13 - 152	27 / F	dusk	rain / wet	55	07	13	05	4	4	Improbable
43 - 002	47 / F	dark - lighted	cloudy / wet	35	01	03	15	0	0	Probable
43 - 004	26 / M	dark	rain / wet	45	01	03	15	0	0	Improbable
43 - 011	31 / F	dark	clear / dry	45	01	03	16	0	0	Probable
43 - 018	22 / F	daylight	rain / wet	55	99	01	05	9	9	Possible
43 - 027	36 / M	dark	cloudy / dry	55	01	13	09	0	0	Probable
43 - 036	33 / M	dark	clear / dry	55	06	01	50	1	1	Possible
43 - 044	unknown	dark	cloudy / wet	55	09	13	06	3	4	Probable
43 - 045	40 / F	dark	cloudy / dry	55	08	13	06	4	3	Possible
43 - 046	33 / M			35	01	01	05	0	0	Improbable
43 - 055	79 / M	dark - lighted	cloudy / dry	45	01	02	15	0	0	Probable
43 - 064	21 / F	daylight	cloudy / wet	35	01	03	17	0	0	Improbable
43 - 092	20 / M	dark	clear / dry	35	08	13	06	3	4	Improbable

Table C-1
Continued

PSU - Case No.	Subject Driver	Light Conditions	Weather / Surface	Speed Limit	GV 14	GV 64	GV65	GV 66	GV 67	Classification
43 - 093	71 / M	daylight	cloudy / wet	55	01	03	17	0	0	Possible
43 - 103	23 / M	dark	clear / dry	55	03	05	10	2	3	Improbable
43 - 104	28 / F	dark	clear / dry	55	03	01	06	2	4	Probable
43 - 105	26 / M	dark - lighted	clear / dry	35	01	13	06	0	0	Possible
45 - 002	16 / M	dark	cloudy / wet	25	08	13	05	3	4	Possible
45 - 004	15 / M	dark	cloudy / dry	30	10	13	10	1	4	Improbable
45 - 034	44 / M	dark	rain / wet	30	03	13	50	2	1	Probable
45 - 039	17 / M	dark	cloudy / dry	30	08	13	13	1	5	Improbable
45 - 045	32 / M	dark	cloudy / dry	30	01	13	11	0	0	Improbable
45 - 070	16 / M	dark	rain / wet	30	01	01	03	0	0	Possible
45 - 071	26 / M	dark	clear / dry	40	01	13	13	0	0	Improbable
45 - 073	25 / F	dark	cloudy / dry	30	01	03	15	0	0	Probable
45 - 115	21 / M	dark	cloudy / dry	30	99	01	15	9	9	Improbable

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